DOCUMENT RESUME

ED 054 966 SE 012 470

AUTHOR Corliss, William R.
TITLE Nuclear Reactors for Space Power, Understanding the Atom Series.
INSTITUTION Atomic Energy Commission, Oak Ridge, Tenn. Div. of Technical Information.
PUB DATE 71
NOTE 52p.; Revised
AVAILABLE FROM USAEC, P. O. Box 62, Oak Ridge, Tennessee 37830 (Free)

EDRS PRICE MF-$0.65 HC-$3.29
DESCRIPTORS *Aerospace Technology; College Science; Instructional Materials; *Nuclear Physics; Physics; Resource Materials; Secondary School Science
IDENTIFIERS Atomic Energy Commission

ABSTRACT

The historical development of rocketry and nuclear technology includes a specific description of Systems for Nuclear Auxiliary Power (SNAP) programs. Solar cells and fuel cells are considered as alternative power supplies for space use. Construction and operation of space power plants must include considerations of the transfer of heat energy to electricity and of waste heat dissipation. The shielding of such plants is important, from both efficiency and safety standpoints. The safety of nuclear material handling in space flight is especially crucial. Various improvements are proposed concerning present power plants. Lists of relevant reading topics and of motion pictures are included. (TS)

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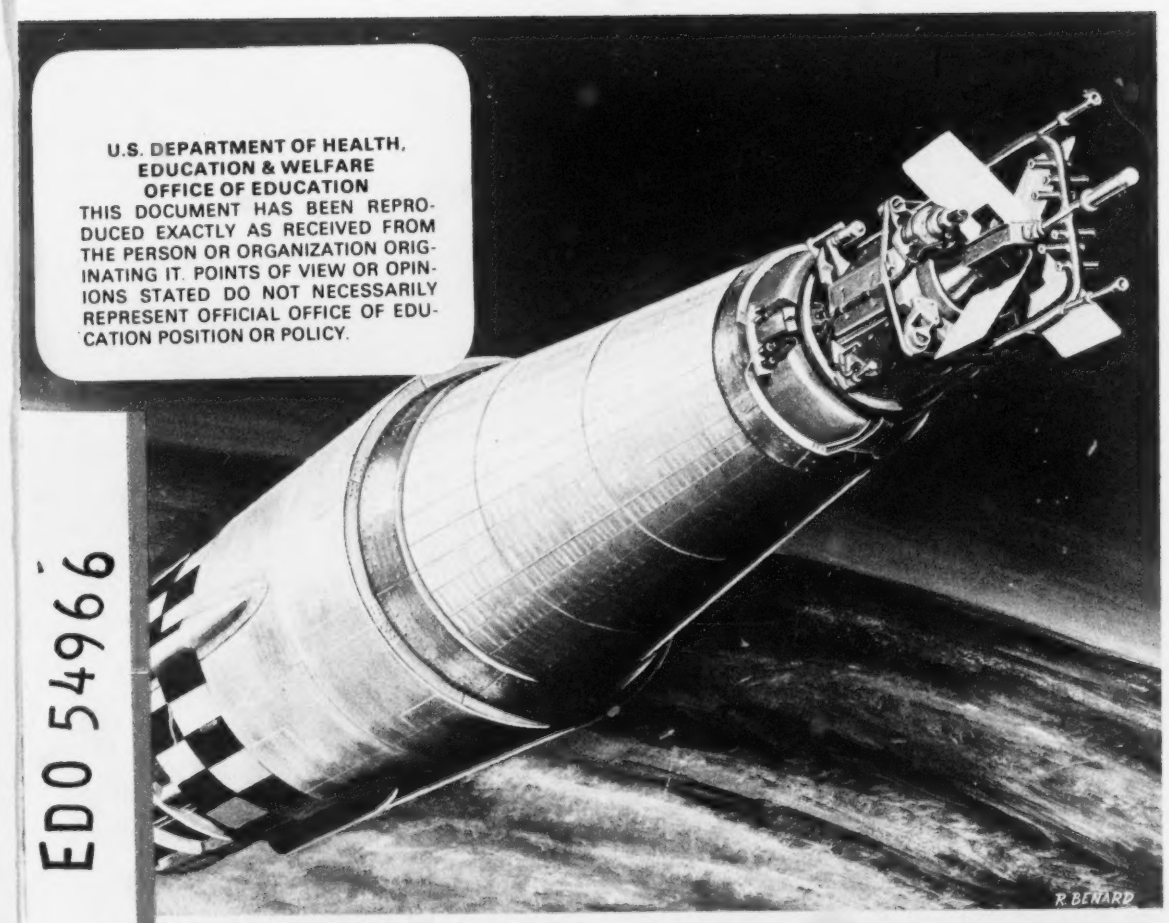

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Nuclear Reactors for Space Power

by William R. Corliss

SE 012 470

The Understanding the Atom Series

Nuclear energy is playing a vital role in the life of every man, woman, and child in the United States today. In the years ahead it will affect increasingly all the peoples of the earth. It is essential that all Americans gain an understanding of this vital force if they are to discharge thoughtfully their responsibilities as citizens and if they are to realize fully the myriad benefits that nuclear energy offers them.

The United States Atomic Energy Commission provides this booklet to help you achieve such understanding.

Edward J. Brunenkant

Edward J. Brunenkant, Director
Division of Technical Information

UNITED STATES ATOMIC ENERGY COMMISSION

Dr. Glenn T. Seaborg, Chairman
James T. Ramey
Wilfrid E. Johnson
Dr. Clarence E. Larson

THE COVER

The cover is an artist's conception of the SNAP-10A space power system, which was launched on April 3, 1965. This was the world's first operation of a nuclear reactor in space. The reactor is the assembly at the right end of the space vehicle.

Nuclear Reactors for Space Power

by William R. Corliss

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United States Atomic Energy Commission
Division of Technical Information

Library of Congress Catalog Card Number: 70-169080
1966;1971(rev.)

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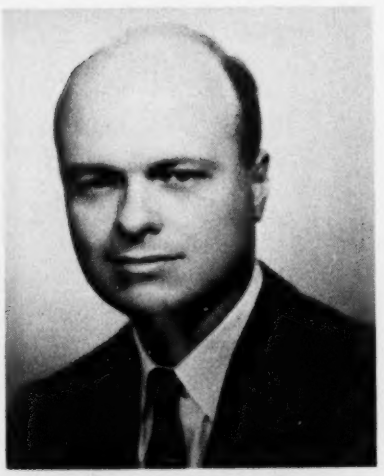


William R. Corliss is an atomic energy consultant and writer with 12 years of industrial experience including service as Director of Advanced Programs for the Martin Company's Nuclear Division. Prior industrial connections were with the Flight Propulsion Laboratory of the General Electric Company and with Pratt & Whitney Aircraft Company. Mr. Corliss has B.S. and M.S. degrees in Physics from Rensselaer Polytechnic Institute and the University of Colorado, respectively. He has taught at those two institutions and at the University of Wisconsin. He is the author of *Propulsion Systems for Space Flight* (McGraw-Hill 1960), *Space Probes and Planetary Exploration* (Van Nostrand 1965), *Scientific Satellites* (Government Printing Office, 1967). *Mysteries of the Universe* (Crowell, 1967), *Mysteries Beneath the Sea* (Crowell, 1970), and coauthor of *Radioisotopic Power Generation* (Prentice-Hall, 1964), *Human Factors Applications in Teleoperator Design and Operation* (Wiley, 1971), and *Man and Atom* (Dutton, 1971), as well as numerous articles and papers for technical journals and conferences. In this series he has written *Neutron Activation Analysis*, *Power Reactors in Small Packages*, *Direct Conversion of Energy*, *Computers*, *Nuclear Propulsion for Space*, *Space Radiation*, and was coauthor of *Power from Radioisotopes*.

Nuclear Reactors for Space Power

By WILLIAM R. CORLISS

INTRODUCTION

Some day a rocket will thrust a manned spacecraft from its parking orbit around the earth and inject it into an elliptical transfer orbit intended to intercept the planet Mars 7 months later. The men in this interplanetary craft will require electrical power for several purposes, for, according to an old rule of thumb, a man can live for only 40 days without food, 4 days without water, and 4 minutes without air. Enough food can and will be carried along on that first Mars journey, but there will not be room enough in the adventurous craft for all the water and air that will be required, unless these vital fluids are used over and over again. The purification and regeneration of water and air will require electricity. So will the craft's instruments and radios. Still more power will be needed to keep the cabin at a livable temperature.

For some long space voyages requiring large power supplies, chemical forms of energy—rocket fuels, battery fluids, and hydrogen—do not have enough energy per unit mass (joules per kilogram or kilowatt-hours per pound). The huge quantities of fuel and oxidizer that would have to be carried along would simply weigh too much. Similarly, solar power has limitations for some missions. The sun's contribution of energy, which is 1400 watts of power per square meter, or 150 watts per square foot, on the earth's surface, will steadily decrease as the spacecraft swings outward toward Mars. Mars is about 1.5 times as far from the sun as the earth is, so the solar-energy density is reduced by a factor equal to the square of 1.5 ($\frac{3}{2} \times \frac{3}{2} = \frac{9}{4}$),

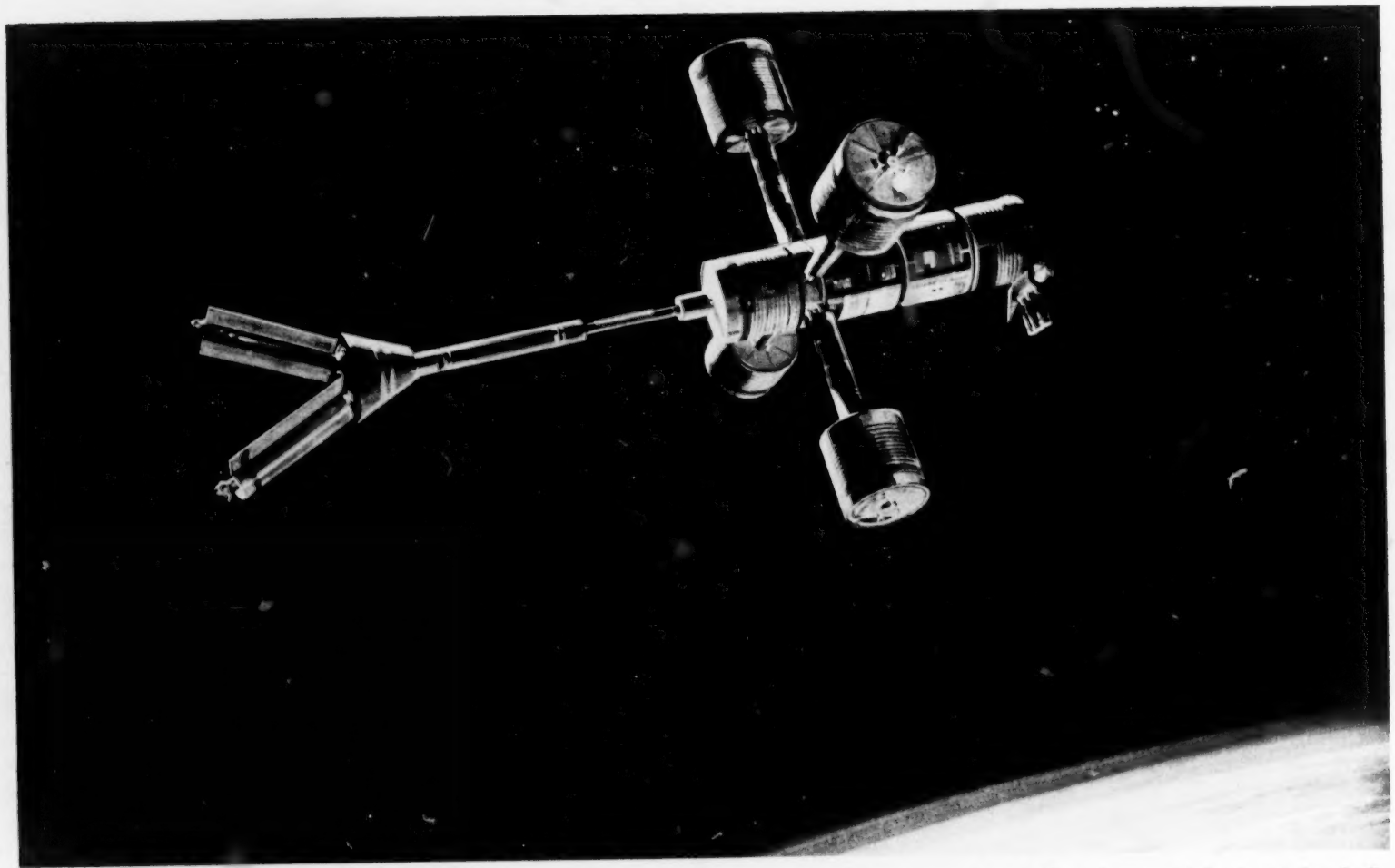


Figure 1 *An artist's concept of an orbital space base powered by nuclear reactors. Reactor module is at far left, with twin reactors at the tips of the Y-shaped booms. Fin-like radiators radiate waste heat to empty space.*

or 2.25. Huge, unwieldly arrays of mirrors or solar cells would therefore be needed to capture enough solar energy for a manned spacecraft operating near Mars. However, small unmanned spacecraft, such as the Mariner Martian probes, find solar cells sufficient for the small amounts of power they require.

In a situation where *large* amounts of power are needed over *long* periods of time, the best source of electricity is a nuclear reactor, which uses energy contained in fissionable uranium. Uranium-235 (^{235}U) contains 100,000 times as much energy per unit mass as the best chemical fuels.

This booklet describes the principles of nuclear-reactor space power plants and shows how they will contribute to the exploration and use of space. It compares them with chemical fuels, solar cells, and systems using energy from radioisotopes.

PUTTING THE ATOM IN ORBIT

It All Started with Feedback

When the chaos of World War II subsided, it was apparent that two important technical developments had occurred. The Germans had developed a large rocket, the V-2. This accomplishment fulfilled the prophesies made years before by the American rocket experimenter, Robert Goddard, the German space pioneer, Hermann Oberth, and the far-sighted Russian, Konstantin Ziolkovsky. The second development, the atomic bomb, introduced a new, extremely compact form of energy that might be used to propel spacecraft, operate equipment, and sustain men on board.

In the late 1940s many scientists and engineers mused about the possibilities of combining the rocket and the atom. Space travel, however, was still a dream, and, besides, nuclear power had not been harnessed even for terrestrial use. Other matters dominated the national interest. An exception to this situation, however, was found in Project Feedback, a cold-war study of military reconnaissance satellites, sponsored by the U. S. Air Force and carried out by the Rand Corporation at Santa Monica, California. During Project Feedback the first serious studies were made

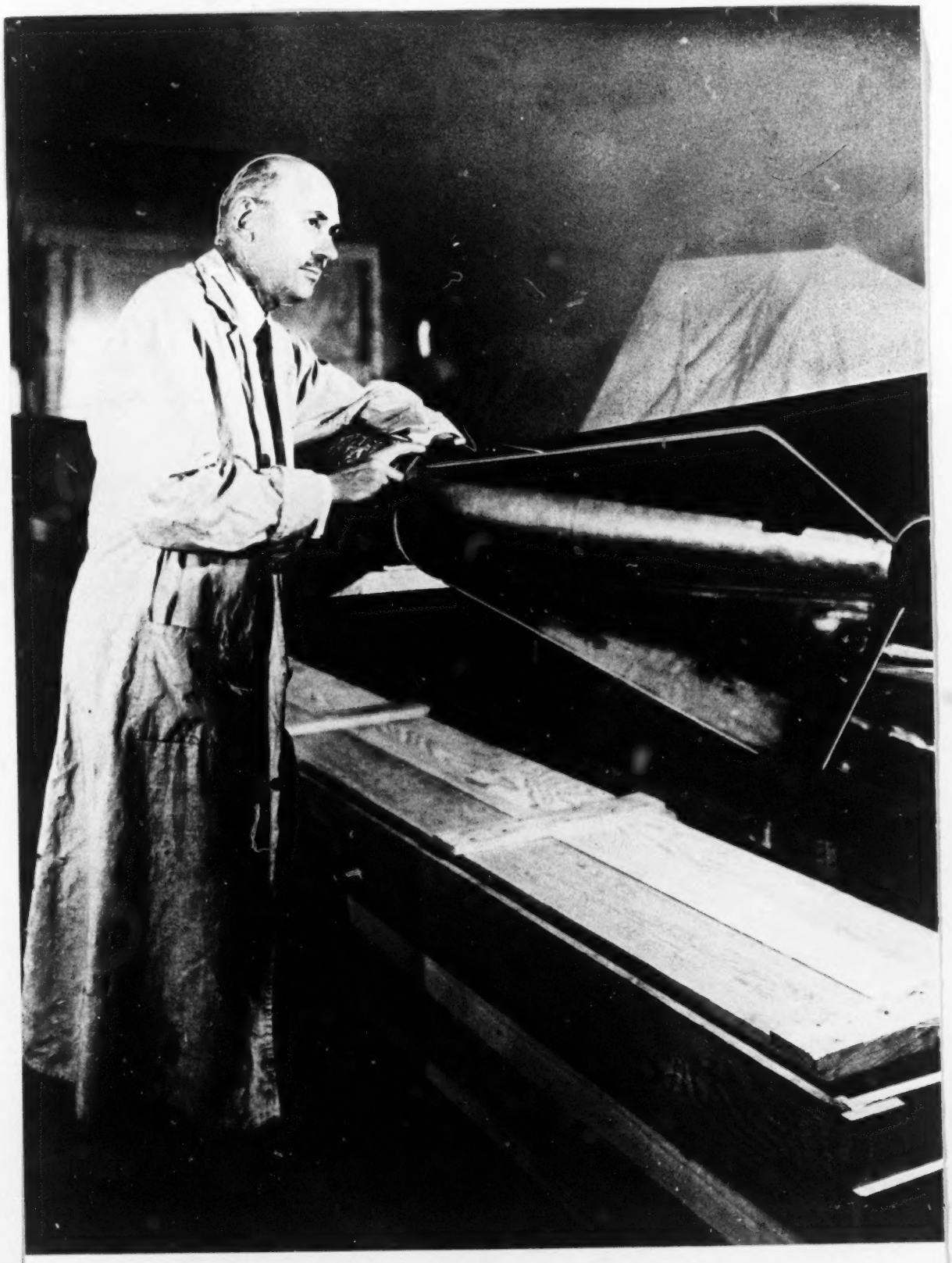


Figure 2 *Dr. Robert H. Goddard in his laboratory in 1932 working with a rocket that he sent to an altitude of 7500 feet (2300 meters).*

of obtaining satellite power from fissioning uranium and from radioactive isotopes.

The relatively high power requirements—a few kilowatts (as much as the output of a small outboard motor)—for some proposed satellites led the U. S. Atomic Energy Commission (AEC) in 1951 to request a series of nuclear-power-plant studies from industry. These studies, completed in 1952, concluded that both fission and radioisotope power plants were technically feasible for use on satellites. At that time there were no rockets capable of launching a satellite, although the first intercontinental ballistic missiles were being developed. But the need for nuclear power in space had been recognized. Theoretical studies continued even though there was not yet any program of space exploration.

Start of the U. S. Space Effort

The official U. S. scientific space effort began in 1955 when President Eisenhower announced the Vanguard satellite program for the International Geophysical Year. The Vanguard satellites weighed but a few pounds and were powered by solar cells. Plans also were moving ahead for much larger satellites, however. Mainly to meet the needs of these devices, the AEC began the SNAP (Systems for Nuclear Auxiliary Power) program in 1955. The Martin Company was chosen to design SNAP-1, which would use the heat from the decaying radioisotope cerium-144 to generate 500 watts of electrical power. Simultaneously, Atomics International Division, North American Aviation, Inc., began the design of SNAP-2, a reactor-heated electrical power plant to produce 3 kw (kilowatts).*

Soon afterward, the development of a reactor-turbogenerator system designed for 35 kilowatts was begun as a joint activity of the Atomic Energy Commission and the National Aeronautics and Space Administration. The SNAP-10, a 300-watt "fission battery", was designed to include a conduction-cooled reactor with thermoelectric elements

*All odd-numbered SNAP power plants use radioisotopic fuel. Even-numbered SNAP power plants have nuclear fission reactors as a source of heat. For more information on the odd-numbered group, see the booklet *Power from Radioisotopes* in this series.

CHRONOLOGY OF SPACE AND NUCLEAR TECHNOLOGY

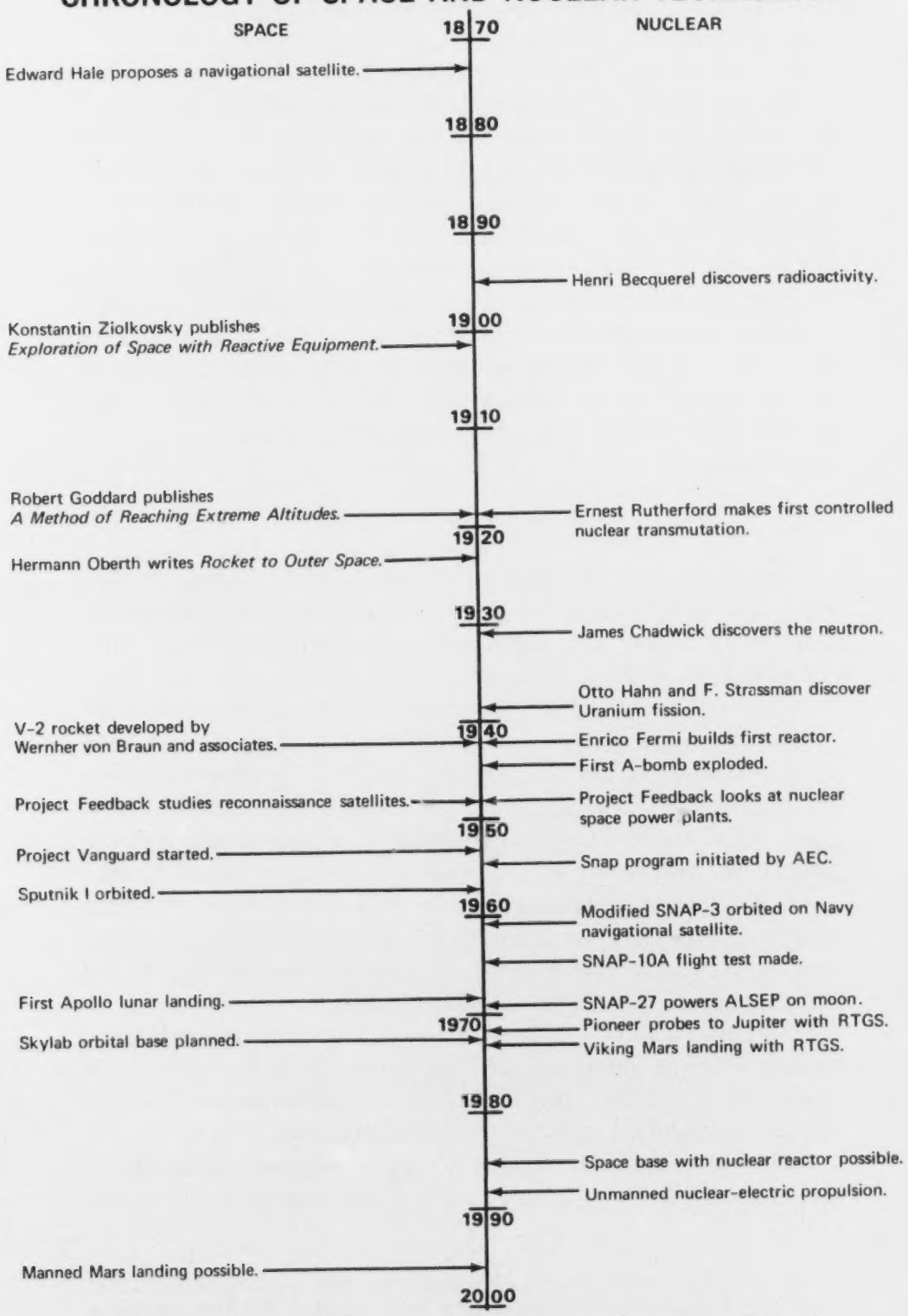


Figure 3

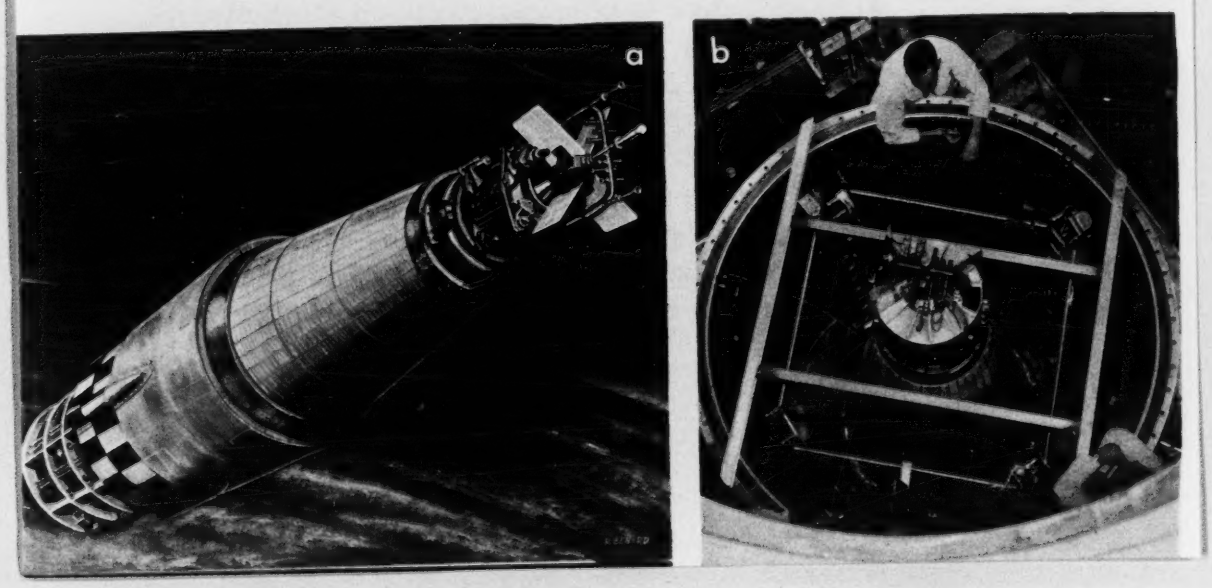
mounted on its surface. Planning for a convection-cooled, SNAP-2 reactor, with a thermoelectric generator on a conical shell behind a radiation shield, began in 1961 to meet a 500-watt requirement of the Department of Defense. It was to be designated SNAP-10A. A more advanced system was labeled SNAP-50. The SNAP Summary Table on pages 8 and 9 shows the status and characteristics of all space nuclear reactor power plants. More detail on each type and its operation will be given in later sections.

SNAP in Space

The first SNAP reactor power plant launched into space was a 500-watt SNAP-10A, which was placed in orbit from Vandenberg Air Force Base, California, on April 3, 1965. An Atlas-Agena launch vehicle injected the satellite carrying the reactor into a near-circular polar orbit with an altitude of about 800 miles (1300 km), the initial period for each journey around the earth being 111.4 minutes. The satellite carried a small ion-propulsion unit and other secondary experiments that used some of the SNAP-10A power. Some of the remaining power was used for the satellite telemetry, and the surplus was dumped into a power absorber.

The reactor functioned successfully for 43 days. Then on May 16, during the satellite's 555th revolution, the ground station tracking the satellite failed to receive telemetry

Figure 4 *(a) SNAP-10A in orbit. It functioned successfully. (See cover.) (b) This earthbound counterpart generated electricity continuously under simulated space conditions for more than a year.*



SPACE POWER REACTOR SUMMARY TABLE

	Electrical power level, kw	Mass, kg (lbs)	Specific mass, kg/kw (lb/kw)	Overall efficiency, %
SNAP-2	3	668 (1470)	223 (490)	5.4
SNAP-4	—	—	—	—
SNAP-6	—	—	—	—
SNAP-8	35	4460 (9800)	127 (270)	7.8
SNAP-10	0.3	—	—	—
SNAP-10A	0.5	427 (960)	908 (2000)	1.6
SNAP-50	100–1000	At 300 kw, 2700 (6000) At 1000 kw, 9000 (20,000)	At 300 kw, 9 (20) (unshielded)	15
Advanced Hydride Reactors	10–100	—	—	Up to 20%
Advanced Liquid-Metal-Cooled Reactor	100–500 plus	—	—	15–25%
In-Core Thermionic Reactor	100–1000	8500 (19,000) at 300 kw	28 (62)†	10–20%

*Two other advanced reactor concepts were investigated in the basic technolog programs: a gas-cooled reactor for use with the Brayton cycle and a boiling potassium reactor for a Rankine-cycle power plant.

†With shielding for an unmanned mission.

signals, and was unable to issue radio commands to the satellite. Signals again were received on the 574th circuit, and it was determined that the satellite telemetry system then was operating on its reserve battery power, and that the reactor power output was zero. Analysis of what had happened indicated that the most probable cause of the reactor shutdown was the failure of a satellite voltage regulator. Meanwhile, in a parallel test, a twin of the orbiting reactor successfully operated on the ground at Santa Susanna, California, without any control adjustments, for more than a year.

Date available	Core type	Core coolant	Energy conversion scheme(s)	Status and possible applications
—	Uranium zirconium hydride	NaK	Rankine-cycle turbogenerator	Discontinued space power plant
—	—	Water	Rankine-cycle turbogenerator	Discontinued undersea power plant
—	—	NaK	Various	Completed series of undersea power-plant studies
—	Uranium zirconium hydride	NaK	Rankine-cycle turbogenerator, mercury working fluid	Component development completed. Power plant concept discontinued in 1970.
—	Uranium zirconium hydride	None	Thermoelectric	Early design using conductive cooling of reactor; changed to SNAP-10A, a convective heat-transfer design
1965	Uranium zirconium hydride	NaK	Thermoelectric	Completed; in orbit April 1965.
1975–1980	Fast, uranium nitride	Li	Rankine-cycle turbogenerator, potassium working fluid	Discontinued in 1965. Replaced by Advanced Liquid-Metal-Cooled Reactor.
Late 1970s	Uranium zirconium hydride	NaK	Thermoelectric and Brayton	SNAP-8 technology improvements. Orbital bases, lunar bases, large unmanned satellites.
1980s	Fast, uranium nitride	Li	Brayton and potassium Rankine	Basic technology program only.* Space and lunar bases, electrical propulsion.
1980s	Fast or with thermal driver	—	Thermionic	Technology program with emphasis on thermionic fuel element. Space base, electrical propulsion.

The first radioisotope power plant was launched successfully in June 1961, when SNAP-3, generating 2.7 watts from plutonium-238 fuel, was orbited on a Navy Transit navigation satellite. This power unit is still operating. Another SNAP-3 and two SNAP-9A power supplies have been launched on later Transits. The SNAP-9As generate 25 watts each.

SNAP program history, however, is more than the collected descriptions of the various power plants. More pointedly, it is the story of the exploration and conquest of difficult and challenging combinations of technologies. As we discuss how the heat from fissioning uranium can be

turned into electricity in space and just what makes a superior space power plant, it will become apparent why effort and money have been channeled into the following technical areas:

1. The construction of very small, lightweight nuclear reactors.
2. The use of liquid-metal coolants to extract heat efficiently from small reactors.
3. The development of thermoelectric and thermionic power generation.
4. The building of small, high-speed turbines and electrical generators.
5. The demonstration, through extensive testing, that nuclear power plants are safe to use in space.

What Makes a Good Space Power Plant?

Rockets, like aircraft, can carry only limited payloads (passengers and instruments). It is always true that a good space power plant is one that does not weigh very much, but this observation considers only one aspect of a complex problem. How much will the power plant cost? Is it safe to use? And, perhaps most important of all, how long will it run without repair or maintenance? We can focus our attention on the evaluation of space power plants by listing such desirable factors as these:

Desirable factor	What it means
Low weight	The power plant's specific mass (mass per unit of power) should be as low as possible.
Low cost	The manufacturing and development costs of the power plant should be as low as possible.
Reliability	The probability should be high that the power plant will run for the specified length of time (usually several years), with little or no human attention, in the presence of meteoroids, high vacuum, and the other hazards of space.
Nuclear Safety	Under no predictable circumstances should the crew or the earth's populace be endangered by radioactivity.
Compatibility	Power-plant characteristics must not require unreasonable restrictions on spacecraft design or operation.
Availability	The power plant must be ready when the rocket and payload are ready for launching.

All these factors, obviously, are coveted by power-plant engineers. The factors, however, are all interdependent, and often one can be improved most effectively only at the expense of the others. Weight, for example, can be significantly reduced by raising the operating temperatures of the power plant, but power-plant equipment might deteriorate more quickly at higher temperatures. At this point the engineer in charge may step in with "trade-offs" to ask, for example, "How much weight-saving must I trade for a month more of operational life?" Ideally, this delicate "balancing act" would result in a low-weight, low-cost, ultra-safe, highly reliable power plant that the spacecraft designer would be delighted to get. In a practical world, however, compromises usually have to be made somewhere by establishing priorities and accepted tolerances for each value. (Meanwhile, the "trade-off" approach also serves as a guide as the search is started for materials that will give the required weight and operational life.)

A Look at the Competition

In general, a spacecraft designer will be satisfied to get *any* power plant that meets his performance specifications, whether the fuel it burns is uranium-235 or kerosene. Nuclear power, however, is in spirited competition with solar and chemical power, and in this competition the "winner" will be the power plant that weighs least when other desirable factors are uniform for all systems.

A typical nuclear-reactor space power plant consists of three major parts: (1) a compact fission reactor that generates heat, (2) an energy converter that transforms some of the heat into electricity, and (3) a radiator that radiates away heat that cannot be used. There is also a heat-transfer fluid that conveys the heat from one part of the power plant to another. As distinguished from its competitors, the solar cell and the fuel cell, a SNAP power plant is a "heat engine", whose operation is described by the laws of thermodynamics.

Except for the Navy Transit satellites and NASA's Nimbus 3 weather satellite, which carry radioisotope power units in addition to solar cells, all of the more than 1000 unmanned satellites and probes launched into space have

used solar cells and batteries for power. The successful American manned spacecraft employ batteries and fuel cells. Just how do these competitors—these other types of power plants—work?

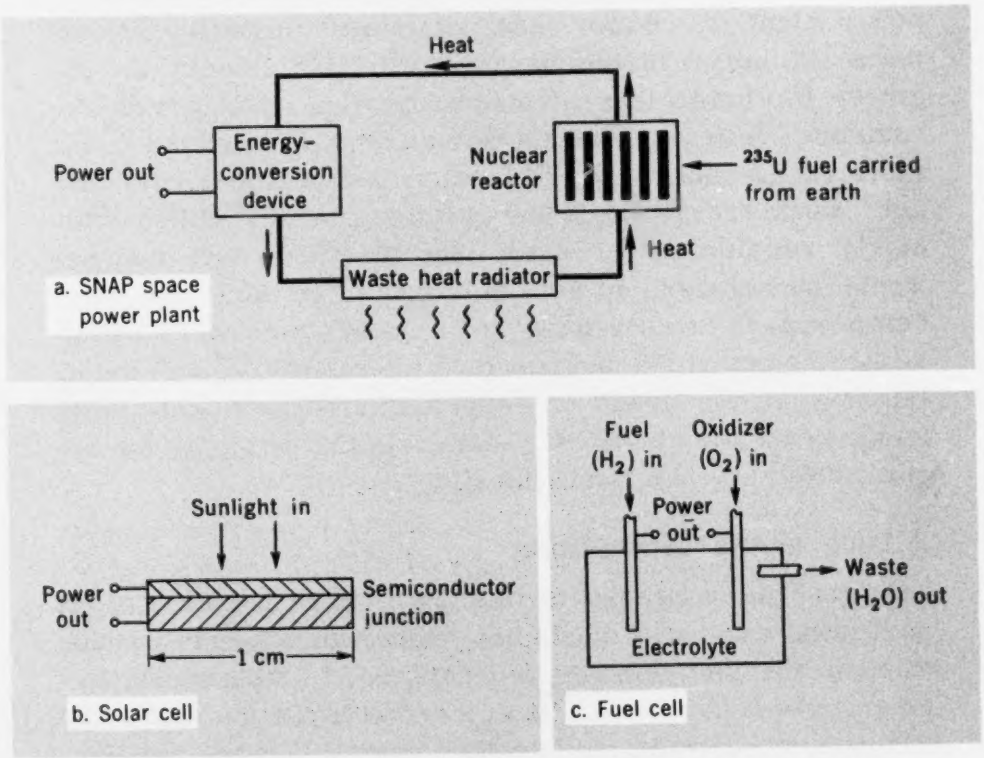


Figure 5 *Comparison of important space power plants. In (a) SNAP converts fission-produced heat to electricity. In (b) the solar cell converts energy of photons to electricity. In (c) the fuel cell converts chemical energy into electricity.*

Let's consider the solar cell. When sunlight hits a solar cell, the absorption of the photons of energy causes separation of electrical charges in a silicon semiconductor, and power is produced.* Solar cells have no moving parts to wear out but are often damaged by radiation in the earth's Van Allen belt. In addition, as satellites carrying solar cells move toward the sun, the extra heat absorbed reduces the cell's efficiency. And, as a spacecraft moves away from the sun, the intensity of solar energy drops inversely as the

*For a fuller explanation see *Direct Conversion of Energy*, another booklet in this series.

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square of the distance. Also, of course, during lunar and planetary nights and under opaque atmospheres, as on Venus, there is no sunlight at all. For many missions, however, solar cells are lighter than present radioisotope and reactor power systems.

Solar cells combined with batteries have satisfactorily powered most satellites so far, but, as power requirements rise higher and higher, larger and larger arrays of solar cells will be needed. This means the big assemblies of cells will have to be deployed, after the craft is in orbit, from their stowed positions within the launch vehicle. Deployment of the butterfly-like solar-cell arrays complicates operations and adds possible sources of failure. Solar cell arrays are, of course, being constantly improved.

Fuel cells are adequate when space missions continue for a month or so. Fuel cells generate electricity directly from the chemical combination of a fuel, like hydrogen, and an oxidizer; the hydrogen–oxygen reaction is $2H_2 + O_2 \rightarrow 2H_2O$ + energy. The fuel cells are, in effect, chemical batteries supplied continuously with fuel. In contrast to solar cells, where the energy source is external and contributes no weight, and nuclear systems, where the weight of the fuel consumed is insignificant, fuel cells need a substantial supply of fluids. Every additional hour of planned operation means that more fuel and oxidizer weight must be aboard at launch time. For space trips of short duration, like the Apollo lunar-landing mission, however, fuel cells have been chosen because they are light and reliable.

Power also can be supplied by radioisotope generators, which convert the energy liberated by radioactive atoms to electricity. Radioisotope systems generally operate in the same power ranges and over the same time periods as solar cells, but have advantages over solar cells for satellite orbits passing through radiation belts, and in areas such as on the moon, where long periods of darkness occur.

There are many missions on which nuclear systems have disadvantages. For example, missions requiring measurement of very low levels of natural space radiation usually will not be able to use a reactor system, because the relatively high radiation from the reactor would interfere with the measurements. For missions at very low power, reac-

tors may not be usable, either. A reactor system has to be of a certain minimum weight before it will produce any power at all; thus, a low-power situation, where low weight is very important, will require solar cells or radioisotope power systems.

Finally, there is a "middle" power range in which solar, radioisotope, and reactor systems all may be useful, and will compete for preference. Figure 6 sums up the situa-

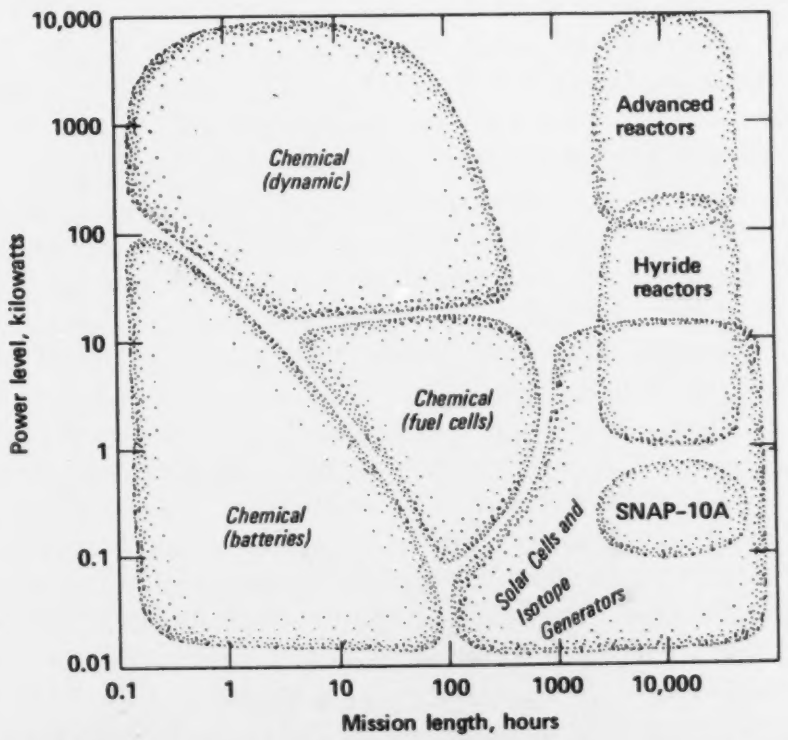


Figure 6 *Areas of superiority for various space power plants. Generally, the higher the power level and the longer the mission, the greater the superiority of nuclear reactor power. Superiority on this chart means least weight.*

tion. Reactor power starts to become competitive on missions needing more than a few kilowatts, and lasting roughly a year or more, because of its weight advantage and its high-energy output. The longer the mission and the higher the power level, the greater the degree of probable reactor advantage. And by the 1980s, some "ambitious" space exploration missions doubtless will be undertaken for which only reactor systems will satisfy the need for power.

What Does "Ambitious" Mean?

It is easy to generalize about the role of nuclear power as long as we use the adjective "ambitious".* To be more precise, however, there are four categories of space missions where reactor power seems appropriate. Almost everyone will agree that they are all truly ambitious:

1. Large orbiting space stations carrying scientists conducting long-term experiments. Launches of nuclear powered bases could begin in the 1980s; however, large solar-cell arrays are also attractive for this kind of application up to power levels of several kilowatts.
2. Lunar exploration after the Apollo landings may involve the establishment of a lunar base. Such a permanent base might well be powered by a small reactor.
3. Manned reconnaissance of the Martian surface, followed by landings, possibly sometime before the end of this century.
4. Large, unmanned earth satellites for radio and television relay, weather prediction, and other military or peaceful missions. (Solar cells may compete here, too.)

Besides these forays, which will be relatively short on the astronomical distance scale, there are proposed long trips to the outer planets. Electrical-propulsion engines, consuming hundreds of kilowatts, will be necessary for exploration at, and beyond the rim of, the solar system, or very close to the sun.

One important feature of some of these anticipated missions will be that they involve keeping men alive and comfortable for long periods of time in an inhospitable environment. It takes a lot of power to sustain men—between 1 and 2 kw per person. It appears that nuclear reactor power will be a strong contender for manned missions that take longer than a few months.

*See conceptual drawings of some "ambitious" spacecraft on pages 24 and 25.

HOW A REACTOR SPACE POWER PLANT WORKS

Fitting the Pieces Together

All SNAP space power plants are heat engines; that is, they generate electricity from heat. Some do this directly without moving parts (SNAP-10A). Others first convert heat into rotary motion (dynamic conversion) and then into electricity by coupling a generator to the rotating shaft. Gasoline-fueled automobile engines and jet aircraft engines are also classified as heat engines. Solar cells and fuel cells are not.

Nature (rather unkindly) dictates that no transformation of heat into another form of energy can be 100% efficient. Science describes this situation in the Second Law of Thermodynamics. According to this law, a portion of each kilowatt of heat produced in a thermodynamic cycle becomes "waste heat". In a practical cycle this unproductive portion must be disposed of. In an automobile most of the waste heat—representing perhaps 80% of the energy in the gasoline—is carried to the radiator and the rest is ejected from the exhaust pipe to the air, and, of course,

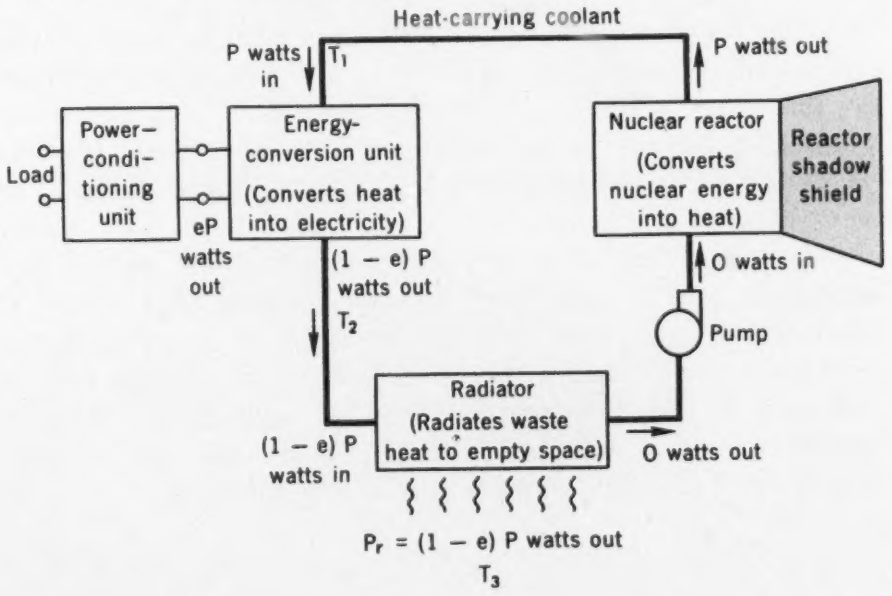


Figure 7 *Schematic diagram of a generalized nuclear-reactor space power plant.*

this heat produces no useful power. However, in space there is no air to cool radiators of the sort used in automobiles, and, because of weight requirements, we cannot afford to use heat engines that continually exhaust fluids. A "closed", recirculating fluid cycle (see Figure 7), rather than an "open" cycle, is required in space. In space flights, then, the only way to get rid of waste heat is to radiate it to cold, empty space, just as the earth itself radiates away heat on a clear winter night. In a space reactor power plant a radiator* cools the hot fluid coming from the energy-conversion unit; the fluid then returns to the reactor for reheating by fissioning uranium and a repeat of the cycle.

Two other power-plant components are shown in Figure 7: Radiation shielding for the crew and instruments and a box labeled "power-conditioning unit". This unit contains all the switches, electron tubes, and regulators needed to provide the craft payload—its passengers and instruments—with the correct voltages, currents, and degrees of electrical regulation.

Important as the shielding and power-conditioning components are, they are not intimately tied to the rest of the power plant by the loop of hot fluid as is the radiator. Still, there are subtle links connecting all five of the major components. Just as we would not design a space power plant independently of the spacecraft, so the five components are designed to interact among themselves. For example, a bigger reactor increases the need for more shielding. The more important of these relations are shown in Figure 8 on page 18.

Megawatts from a Wastebasket

If you bring a few pounds of ^{235}U together very rapidly, you can create a nuclear explosion—an uncontrolled release of energy from fissioning ^{235}U. In any atomic power plant, the trick is to slow down the rate of energy release, or, in other words, control the reaction; then it is necessary to find a way to extract the tremendous quantities of heat that are generated.

*Note this is a radiator for *heat*, not nuclear radiation.

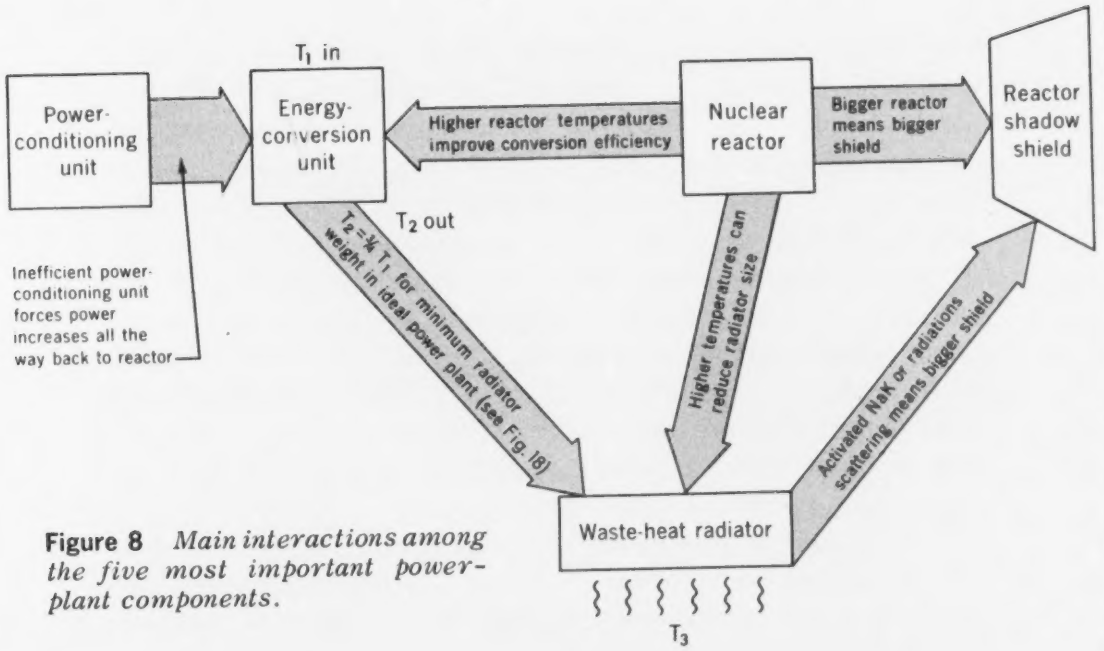

T_1 in
Power-conditioning unit
Energy-conversion unit
Higher reactor temperatures improve conversion efficiency
Nuclear reactor
Bigger reactor means bigger shield
Reactor shadow shield
T_2 out
Inefficient power-conditioning unit forces power increases all the way back to reactor
$T_2 = \frac{1}{4} T_1$ for minimum radiator weight in ideal power plant (see Fig. 18)
Higher temperatures can reduce radiator size
Activated NaK or radiations scattering means bigger shield
Waste-heat radiator
T_3

Figure 8 *Main interactions among the five most important power-plant components.*

The rate at which fission occurs in ^{235}U or in any other fissionable isotope, depends upon how the reactor's neutron "economy" is managed. Neutrons are the medium of exchange in a nuclear reactor economy. When a single ^{235}U nucleus fissions spontaneously, two or more neutrons are released, in addition to a substantial amount of energy. Collectively, the two released neutrons can cause *more than one* additional fission in the surrounding uranium in less than one thousandth of a second. Each new fission can repeat the process. Therefore, if an average of only 1.2 secondary fissions occurred as a result of each initial fission, 1.2^{1000}, or 10^{79}, fissions would (theoretically) occur in 1 second. The energy release would be immense. The essence of reactor control is: To keep the power level in a nuclear reactor steady, the neutrons released in each fission should go on to cause *precisely one more* fission. When this occurs, the reactor is self-sustaining or "critical". The reactor power output may be raised or lowered by permitting slightly more or slightly less than one additional fission to occur until the desired power level is achieved. The "just critical" condition can then be reestablished by control-element adjustments.

Neutron economy, like dollar economy, is controlled by balancing income and outgo. Three things can happen to

each fission-generated neutron: (1) It can go on to cause another fission and, in the process, release more than one new neutron (profit). (2) It can be absorbed in a nonfission reaction with atoms in the coolant, the structure, or even uranium itself* (loss). (3) It can bounce off (scatter) atoms in the reactor without being absorbed and ultimately escape from the fuel region altogether (loss).

In most small nuclear reactors, like SNAP-2 and SNAP-10A, the neutron population is controlled by varying the number of neutrons that are permitted to escape. The uranium fuel region is surrounded by a good neutron reflector like beryllium or beryllium oxide. The reactor power level is reduced by temporarily opening up the reflector and allowing more neutrons to stream through the openings and escape. (See Figure 9.) The power level is raised by closing the reflector.

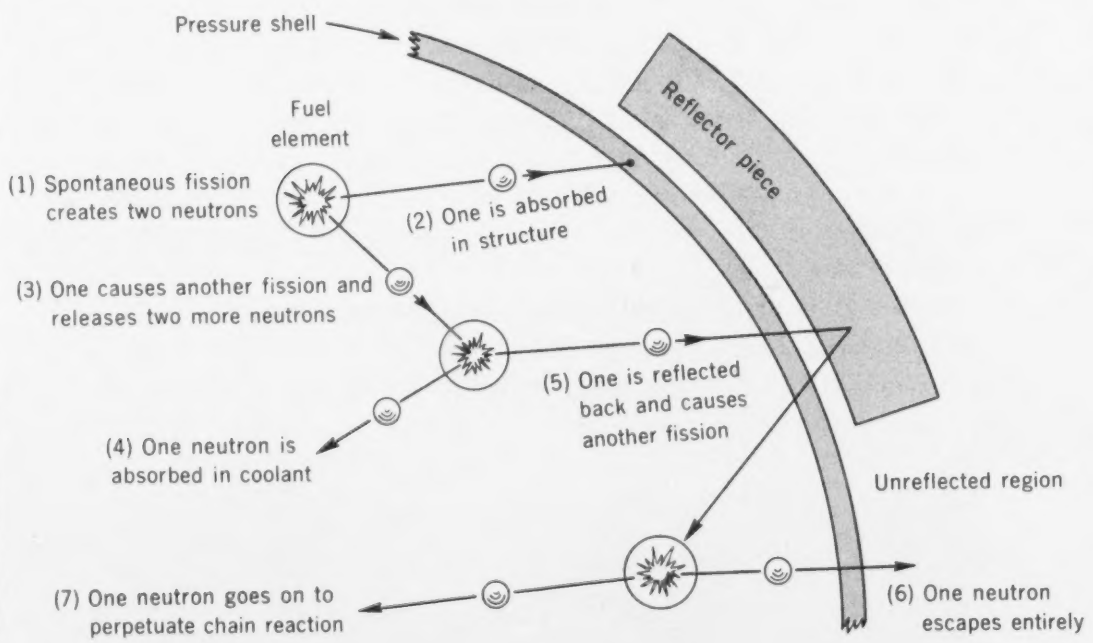

Pressure shell
Fuel element
(1) Spontaneous fission creates two neutrons
(2) One is absorbed in structure
Reflector piece
(3) One causes another fission and releases two more neutrons
(4) One neutron is absorbed in coolant
(5) One is reflected back and causes another fission
Unreflected region
(7) One neutron goes on to perpetuate chain reaction
(6) One neutron escapes entirely

Figure 9 *Neutron economy in a reactor core. The illustration assumes two neutrons are born in each fission. The reactor is just critical (self-sustaining) when each fission causes another fission.*

*All neutron reactions with uranium do not cause fission. Sometimes ^{235}U can be converted to ^{236}U with release of gamma radiation.

A lump of pure ^{235}U about the size of a baseball can be made critical, but can a practical power reactor be made this small? It cannot, if useful power is to be extracted. If a lump of fissioning uranium is to generate significant power, holes have to be made in it for the passage of a fluid that will take the heat away to the energy-conversion unit where electricity is produced: The "baseball" has to be bigger when coolant holes are provided. Moreover, the holes must be lined with a tough metal to protect the uranium fuel from corrosive attack by the heat-transfer fluid. A still larger core of uranium is needed because, in order to reduce the inventory of expensive ^{235}U (approximately $5000/lb or $11,000/kg), a neutron "moderator" must be added to slow the fast, fission-generated neutrons down to speeds at which they stimulate additional fissions. By the time the coolant holes, protective coatings, and moderator have been added, SNAP reactor cores are the size of a small wastebasket.

Instead of starting with massive pieces of uranium fuel and drilling holes through them, a reactor designer makes *fuel elements* that are long, slender cylinders or plates of

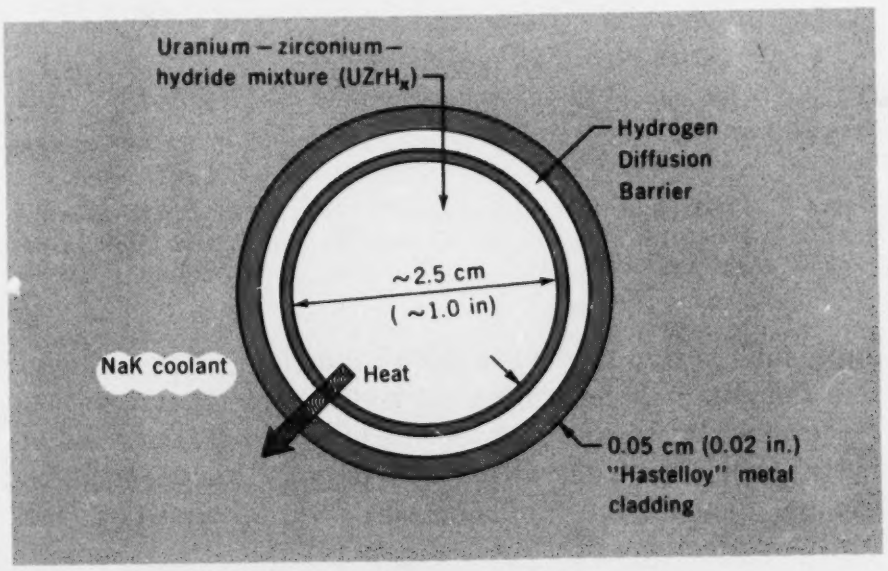


Figure 10 *A typical fuel element for a SNAP hydride core reactor.*

fuel and moderator (uranium–zirconium–hydride [U–Zr–H_x] in many SNAP reactors). The elements are clad with metal sheaths to protect the contents from the coolant and prevent dispersal of the radioactive by-products of fission. Fuel elements are then assembled to make the core, and room is left among them for the coolant to flow. Next, the core is housed in a strong metal container called a reactor

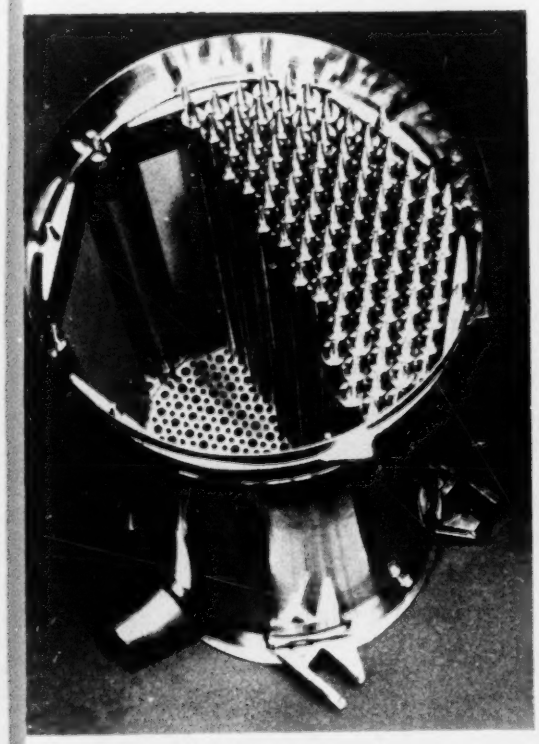


Figure 11 *A SNAP-8 reactor core showing some of the cylindrical fuel elements, clad in a nickel-steel superalloy, in place. NaK coolant will flow in the spaces between elements. The core is approximately 20 centimeters (8 inches) across.*

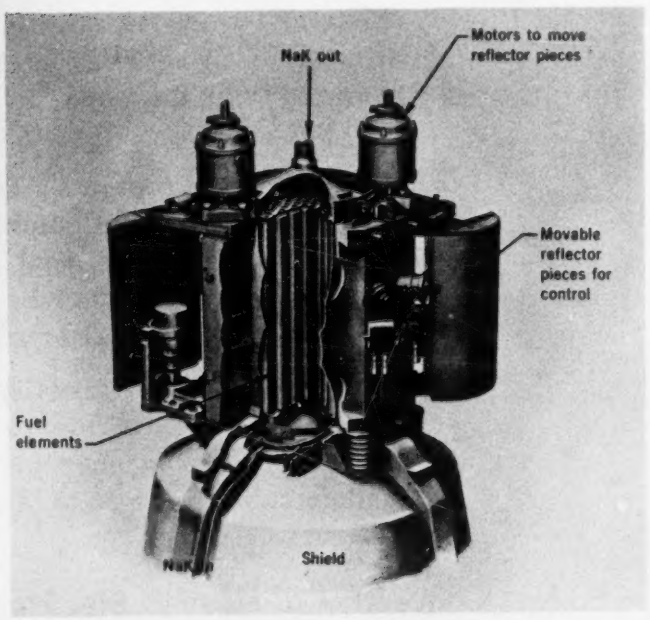


Figure 12 *The SNAP-2 reactor. Movable reflector pieces vary the rate of power production.*

vessel. The pumping of a good heat-transfer fluid, like molten lithium or a sodium–potassium alloy called NaK (pronounced "nack"), through this compact bundle of fuel elements transports many kilowatts of heat to the energy-conversion unit.

Finally, a means for control is provided. On SNAP reactors, movable reflector pieces are mounted outside the reactor vessel, as shown in Figure 12. Control can be maintained by these cylindrical reflector elements. The cylindrical control drums are made of an effective neutron reflector, beryllium or beryllium oxide. Rotating the drums outward causes more neutrons to escape and reduces the reactor power level. (It should be noted that it is not always necessary to put moderator material into the reactor.)

All space reactors are termed "compact" to distinguish them from commercial power reactors, which are hundreds of times larger. Compactness, of course, reduces not only the weight of the reactor but also the weight of the radiation shield. The following factors make a nuclear reactor compact.

1. Almost pure ^{235}U is used for fuel rather than natural uranium, which is only 0.7% ^{235}U and 99% ^{238}U; this eliminates or greatly reduces the large amount of heavy ^{238}U in the core. In many earthbound reactors the proportion of ^{235}U to ^{238}U is much smaller.
2. Liquid-metal coolants (like NaK) are employed. Water, used in most commercial plants, is not as effective in removing heat and, because of its high vapor pressure, cannot be used at the high temperatures needed for SNAP systems.
3. Reactor control is usually accomplished by varying the effectiveness of the reflector rather than inserting strong neutron absorbers directly among the fuel elements, as in the case of most commercial reactors.

Conversion of Heat to Electricity

Given a fast stream of very hot liquid metal emerging from a SNAP core, how can we best turn its energy into electricity? Remember that we cannot possibly turn all of it into electricity because, according to the Second Law of Thermodynamics, 100% efficient heat engines are not possible. In fact, if the engine is too efficient, the conversion

unit will extract too much heat from the coolant, and the coolant temperature will be lowered to the point where the waste heat will be difficult to radiate away in the radiator. We can use the equation for the efficiency of an ideal heat engine to guide our thinking:

$$e = \frac{T_1 - T_2}{T_1}$$

where e = the Carnot efficiency (after the Frenchman, Sadi Carnot, who developed the formula for the ideal heat engine)

T_1 = the temperature of the heat source, in °K or °R*

T_2 = the temperature of the heat sink (radiator), in °K or °R

SNAP-10A makes use of this equation in the simplest way. The hot liquid metal is pumped past thermoelectric couples that convert less than 2% of the heat into electric-

*Degrees on the Kelvin scale (°K), that is, degrees on a scale in which zero is equal to −273.15° Centigrade, or on the Rankine scale (°R), in which zero is −459.69° Fahrenheit.

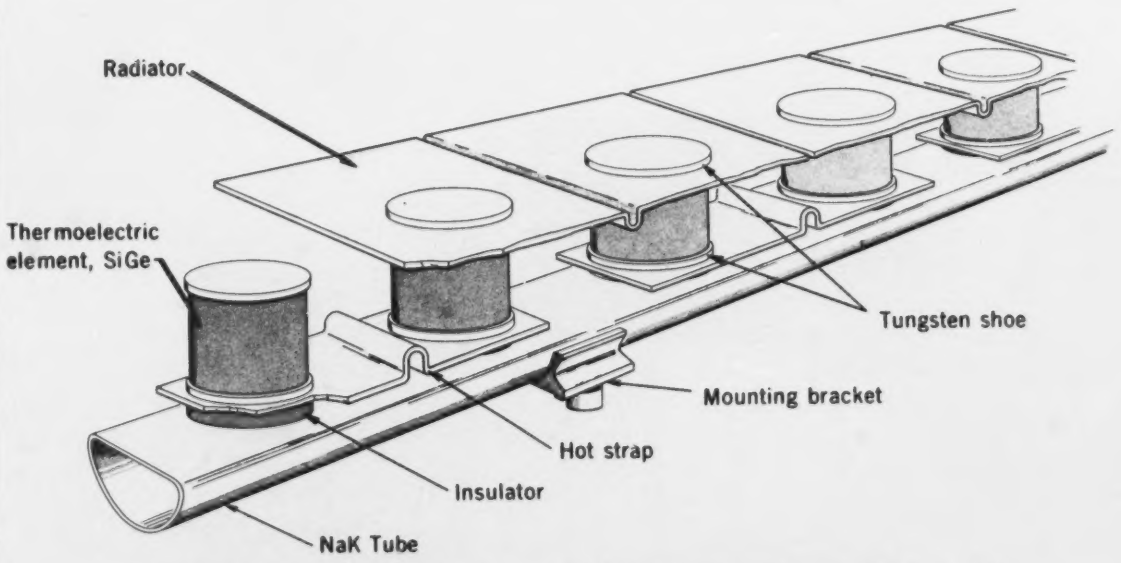
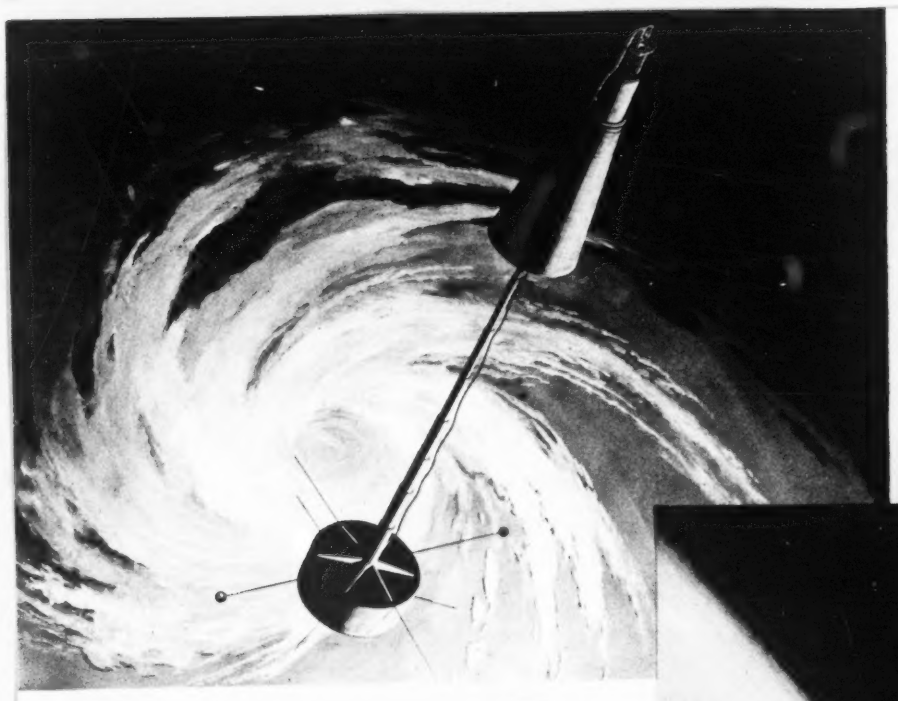


Figure 13 *The SNAP-10A thermoelectric converter module. Heat brought in by hot NaK is partially converted to electricity in the thermoelectric elements. Waste heat is radiated to empty space.*



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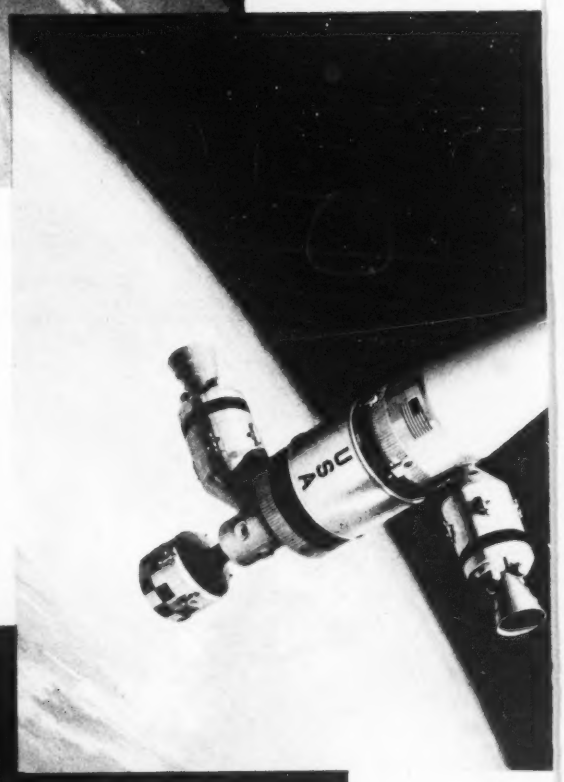
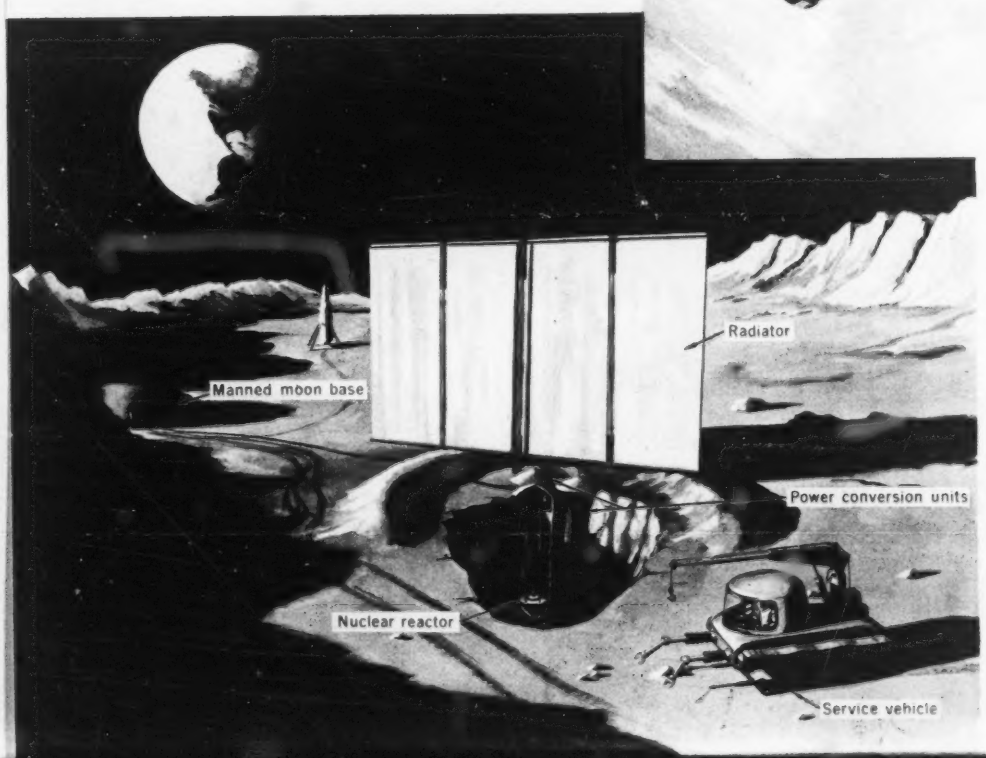
An advanced meteorological satellite in orbit over an earth hurricane. The reactor is at the very top with the conical radiator beneath it. The dumbbell shape helps stabilize the satellite.





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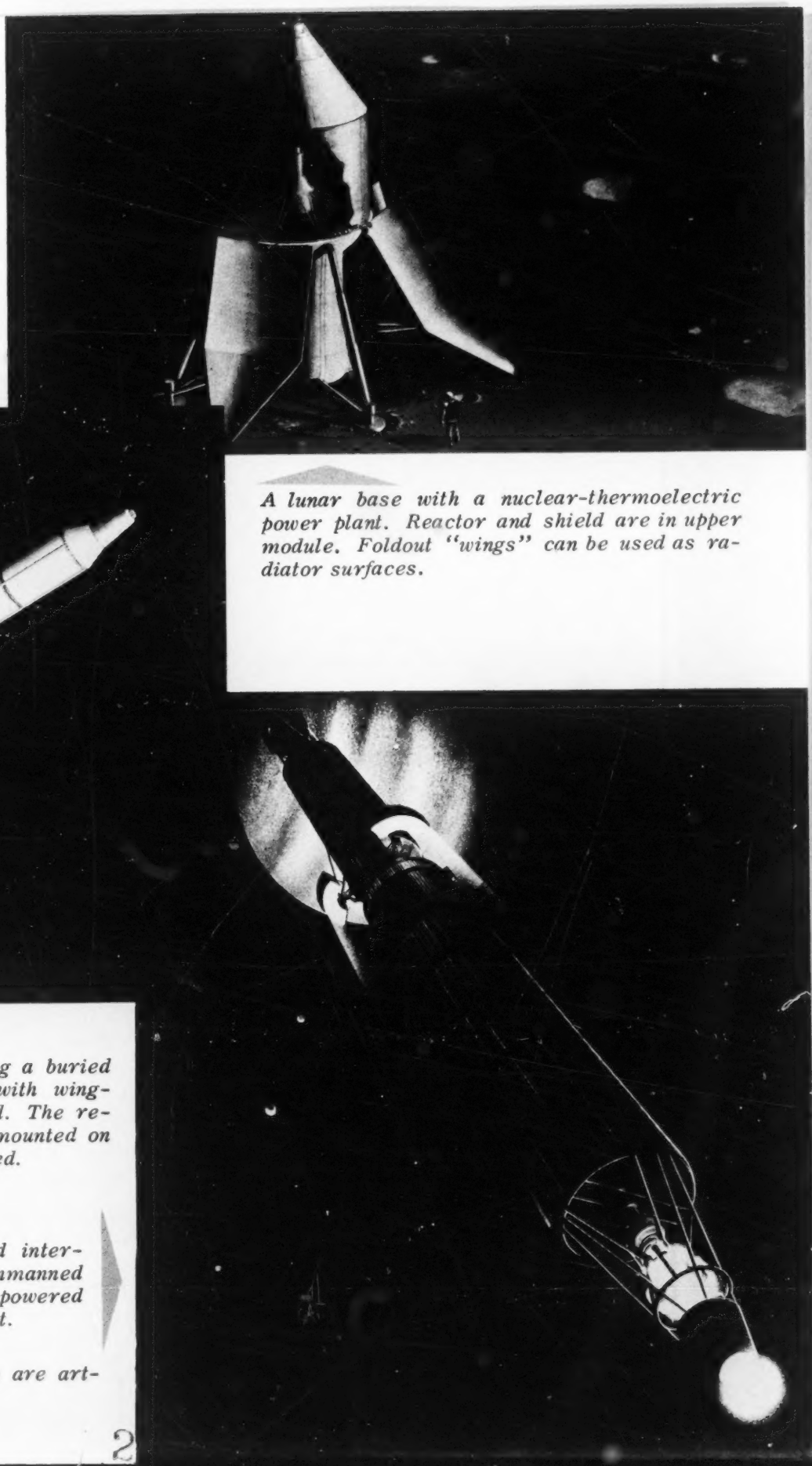

A lunar base with a nuclear-thermoelectric power plant. Reactor and shield are in upper module. Foldout "wings" can be used as radiator surfaces.

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ity. Conveniently, the SNAP-10A thermoelectric couples are mounted directly between the hot NaK pipes and the radiator.

Figures 13 and 14 show how deceptively simple the concept of thermoelectric conversion of energy is. A semiconductor material, such as silicon-germanium (SiGe), is

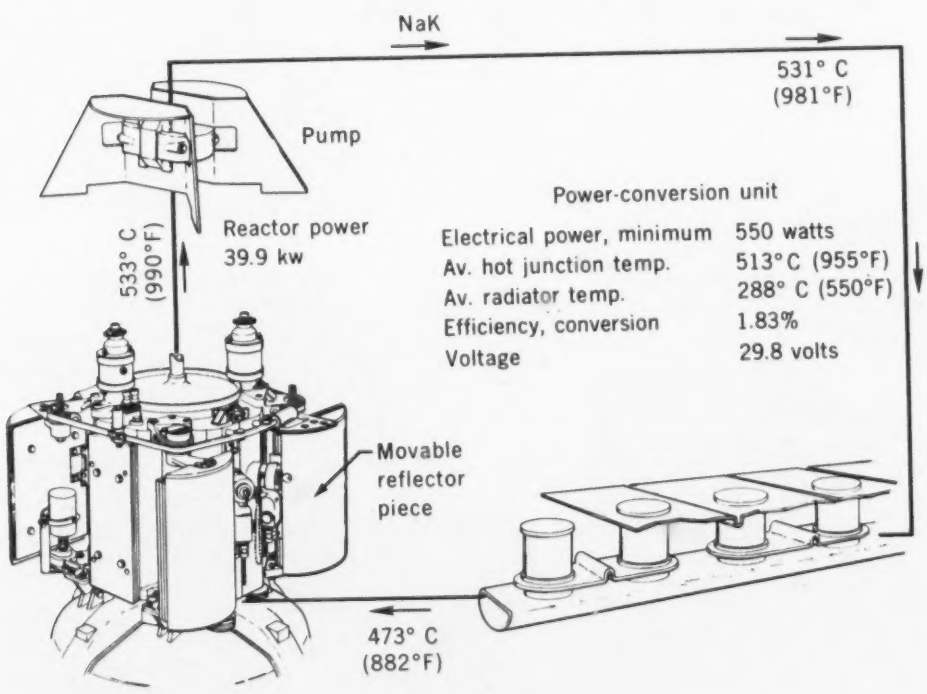

Figure 14 *Schematic diagram of the SNAP-10 reactor and power-conversion unit.*

heated at one end and cooled at the other, and production of electricity results.* The fabrication of lightweight, rugged, efficient arrays of hundreds of tiny cylinders of this rather brittle material has been a difficult engineering task, although the success of SNAP-10A shows it can be done. Because the weight of SiGe is relatively high and the efficiency low (less than 2% in SNAP-10A), thermoelectric conversion is expected to be used only at low power levels. Thermoelectric elements, utilizing such materials as lead tel-

*See *Direct Conversion of Energy*, another booklet in this series, for an explanation of the process.

luride, have achieved efficiencies approaching 6% at about 600°C (1100°F). These developments should extend the range in which thermoelectrics are competitive into the tens of kilowatts.

For higher power levels, dynamic conversion should be considered. In this concept the hot liquid metal from the reactor is directed into a heat exchanger, where its contained energy is transferred by conduction and convection to the heat transfer medium (or "working fluid") in the power conversion loop. SNAP-2 is a good example of a dynamic conversion system. Here, NaK occupies the primary loop, and mercury the secondary. (See Figure 15.) The mercury is boiled in the heat exchanger, and the resulting hot mercury vapor is piped to a turbine, where it strikes and expands against the turbine blades and makes them turn. The turbine shaft revolves, and this movement drives an attached electric generator. This arrangement, involving a turbine–generator combination is called a turbogenerator. The expanded, cooler vapor passes next into the condenser, where it condenses back to a liquid as

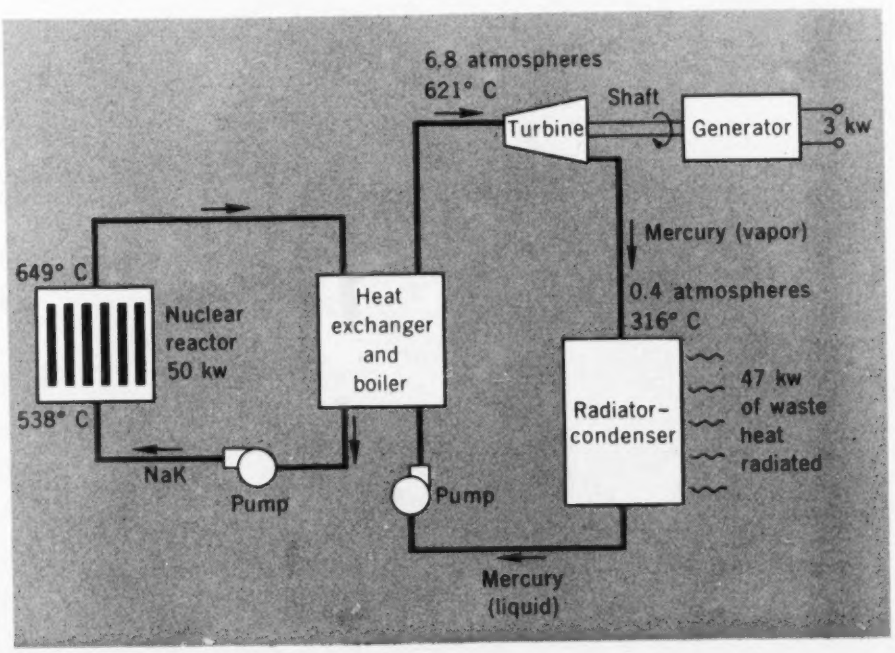

Figure 15 *Schematic diagram of SNAP-2 nuclear power plant.*

more heat (the waste heat) is extracted from it. The liquid mercury flows through a pump and back to the heat exchanger–boiler to be heated again. This energy conversion scheme is called the Rankine cycle.

A turbogenerator is an efficient device. In large, earth-based commercial power plants, this arrangement takes 30% or more of the heat and energy of a fluid and converts it into electricity. Because the emphasis in space is on compromise, for area and weight, rather than efficiency, efficiencies are generally between 8% and 17% in Rankine cycle space power plants, a level that is still considerably higher than that obtainable from thermoelectricity. At power levels over a few kilowatts, turbogenerator systems are lighter per generated kilowatt than thermoelectric systems. We therefore find them at the upper end of the power spectrum (Figure 16).

The SNAP-2 and SNAP-8 power systems employed a two-phase fluid to convert heat into electricity. As men-

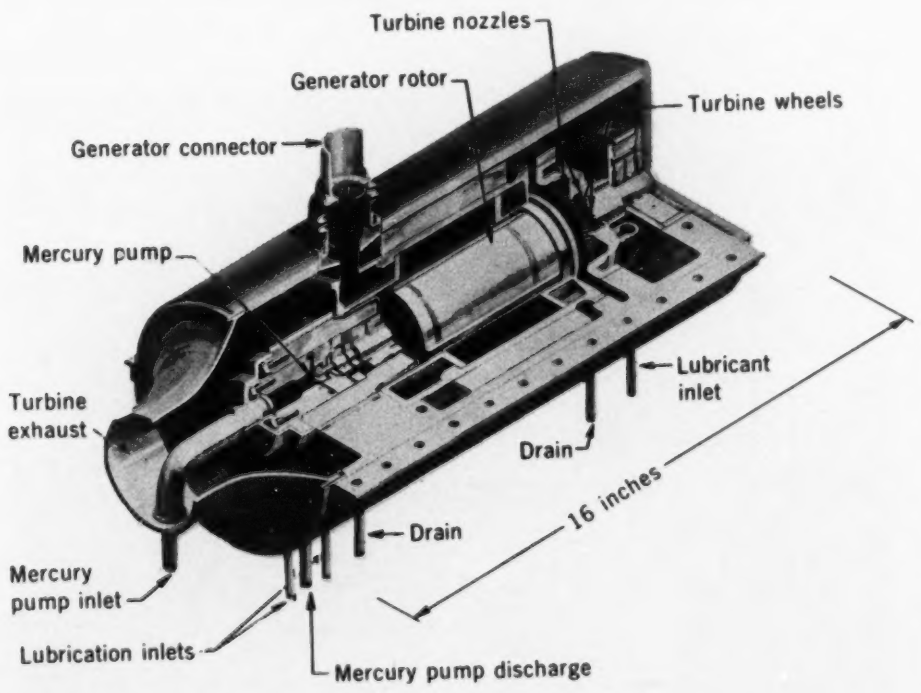

Figure 16 *Combined turbine-generator-pump unit.*

tioned earlier, the thermodynamic process involved is called the Rankine cycle. Another very attractive power conversion cycle exists called the Brayton cycle. Somewhat simpler than the Rankine cycle, the Brayton cycle utilizes a gas, such as one of the noble gases, and there is no phase change from liquid to vapor and back again. The relative merits of these two contending thermodynamic cycles are discussed in a later section entitled "Brayton Versus Rankine".

Getting Rid of Waste Heat

In the early days of space power engineering, when concepts were less advanced, the radiator was given less attention than it is now. To be sure, everyone recognized that there *was* waste heat and that it *had* to be dissipated or the spacecraft would melt. It is now apparent, however, that the radiator will often be the most massive component in the entire power plant. It is heavy because of the large amount of radiator area needed. The Stefan-Boltzmann Law* enables us to calculate the heat radiated from a given area by this equation:

$$P_r = \sigma E A (T_2^4 - T_3^4)$$

where P_r = the power radiated, watts,
σ = the Stefan-Boltzmann constant (5.67×10^{-8} watts/m^2-°K^4 or 5.02×10^{-10} watts/ft^2-°R^4),
E = the emissivity of the radiator surface,
A = the radiator area, m^2 or ft^2,
T_2 = the radiator temperature, in °K or °R, and
T_3 = the effective temperature of outer space, in °K or °R.

Usually T_3 is almost zero, except in the vicinity of large, warm bodies, such as the sun and earth. At the SNAP-10A

*Named for the Austrian physicists, Josef Stefan (1835–1893) and Ludwig Boltzmann (1844–1906).

radiator temperature of 321°C (610°F), 5.8 m^2 (62.5 ft^2) of radiator area are needed to radiate away approximately 40 thermal kilowatts of waste heat. Not only is a large area needed but also the metal walls of the radiator have to be thick enough to withstand the puncturing effects of the high-speed micrometeoroids that pervade outer space. The best way to reduce radiator weight, as suggested by the Stefan-Boltzmann Law, therefore, is to increase the radiator temperature, T_2.

An instructive situation involving T_2 now comes to light. Since radiator area (and therefore weight) is proportional to $1/T_2^4$, a little increase of T_2 helps a lot (notice that 4th power!); but the Carnot equation (page 23) tells us that this increase also reduces the efficiency of the heat engine, assuming T_1 is kept fixed (but here T_2 is only to the first power!). By using minimization techniques (from calculus), we can show that minimum radiator area occurs when $T_2 \approx \frac{3}{4}\ T_1$ and e ≈ 25%. Figure 18 shows this qualitatively.

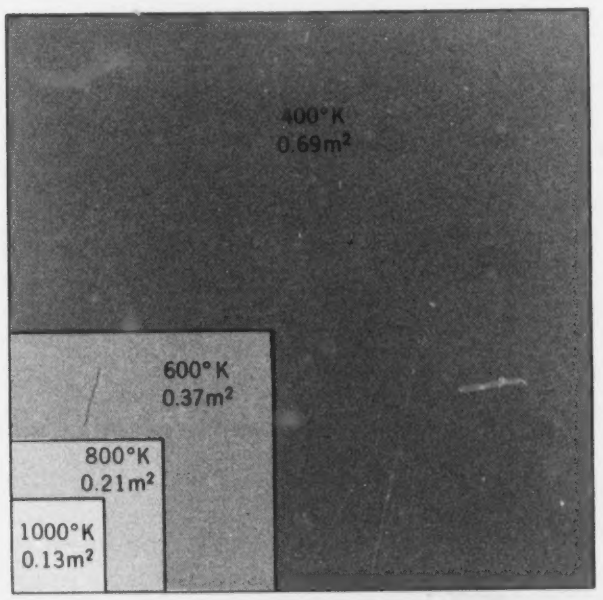

Figure 17 *Relative areas required to radiate waste heat to empty space at different temperatures. Increasing the radiator temperature rapidly brings down area and weight. (Figures given are calculated for 1 kilowatt of heat and perfect emissivity.)*

Even though weight is at a minimum, it is apparent from the power-plant photographs in this booklet that the radiator is still a bulky piece of equipment. The photos also show the favorite arrangement of power-plant components on a spacecraft, that is, the use of conical radiators, with the reactor isolated at the end farthest removed from the payload, so as to provide protection against nuclear radiation by distance.

Space radiators could also be split into several parallel sections so that, if a meteoroid should puncture any one of them, valves could be closed and the others would continue to operate. This stratagem would preclude the complete loss of coolant and hence of power, spacecraft, mission, and men. For effectiveness, leak detectors would be required in each valved section to command valves to close automatically in the event of a puncture.

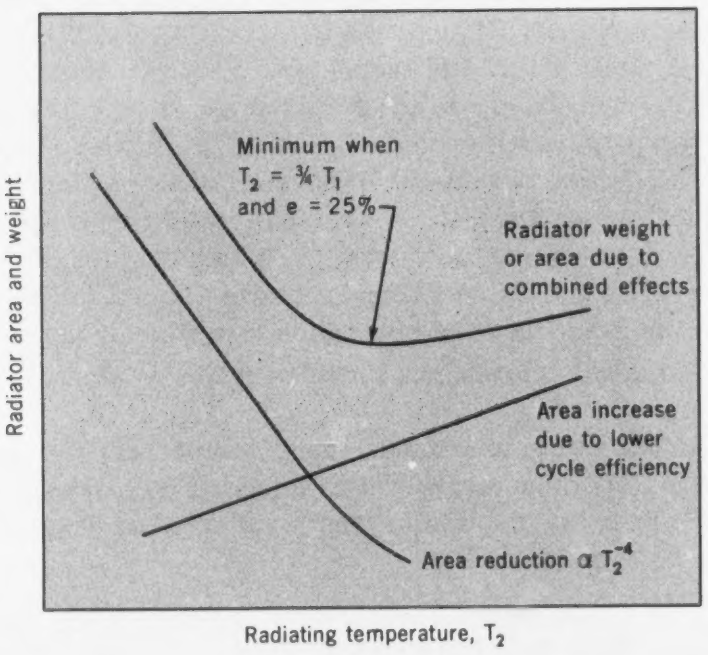

Figure 18 *Sketch showing qualitatively how increasing the temperature (T_2) decreases radiator area on one hand due to the Stefan-Boltzmann Law, but increases it on the other due to loss of cycle efficiency, as described by the Carnot efficiency equation. (T_1 is assumed to be constant.)*

During the 1960s, a novel heat transfer device called the "heat pipe" entered the space power scene. Basically, the heat pipe is a long channel (usually a cylindrical pipe) in which heat is carried by a two-phase fluid from one end to the other. At the hot end, the fluid vaporizes, flows down the heat pipe as a vapor, and then condenses at the cold end. The liquid phase then returns to the hot end via a wick structure. The heat pipe is self-contained and, since no motors or pumps are necessary, highly reliable. It is mentioned in connection with space radiators because it may represent a simple, reliable way of transferring waste heat from the energy conversion device to an external radiator.

Early power-plant designers pondered another question: Will vapor condense in a radiator under zero gravity conditions? On the earth's surface, the force of gravity aids in condensation first by pulling the vapor atoms to the heat-transfer surfaces of the radiator, where they are condensed, and then by causing the liquid to run uniformly down the surfaces. This action brings about a stable vapor–liquid movement in the condenser. Under zero gravity, though, it was expected that unstable movement through the tubes might occur because of irregular flow of "slugs" of liquid. Radiator designers tapered the tubes to stabilize condensation as well as to assist in weight reduction. Experiments conducted on "zero-g" trajectory flights by Air Force planes and on suborbital missiles have indicated that stable condensation does take place in a state of weightlessness! More experience is needed with full-scale equipment, however.

Far from being a simple, inert component, the power-plant radiator has turned out to be a difficult device to design as well as a major weight and volume factor in the overall power plant.

Shielding Men and Equipment

The neutron–fission reaction yields many gamma rays and neutrons. In addition, the unstable fission-product atoms produced in the fission process emit more gamma rays. Sensitive equipment, such as transistors and other

electronic devices, must be protected against these radiations. So must the men aboard a nuclear-powered spacecraft.

Since the intensity of radiation drops off as the square of the distance from the reactor, the reactor usually is iso-

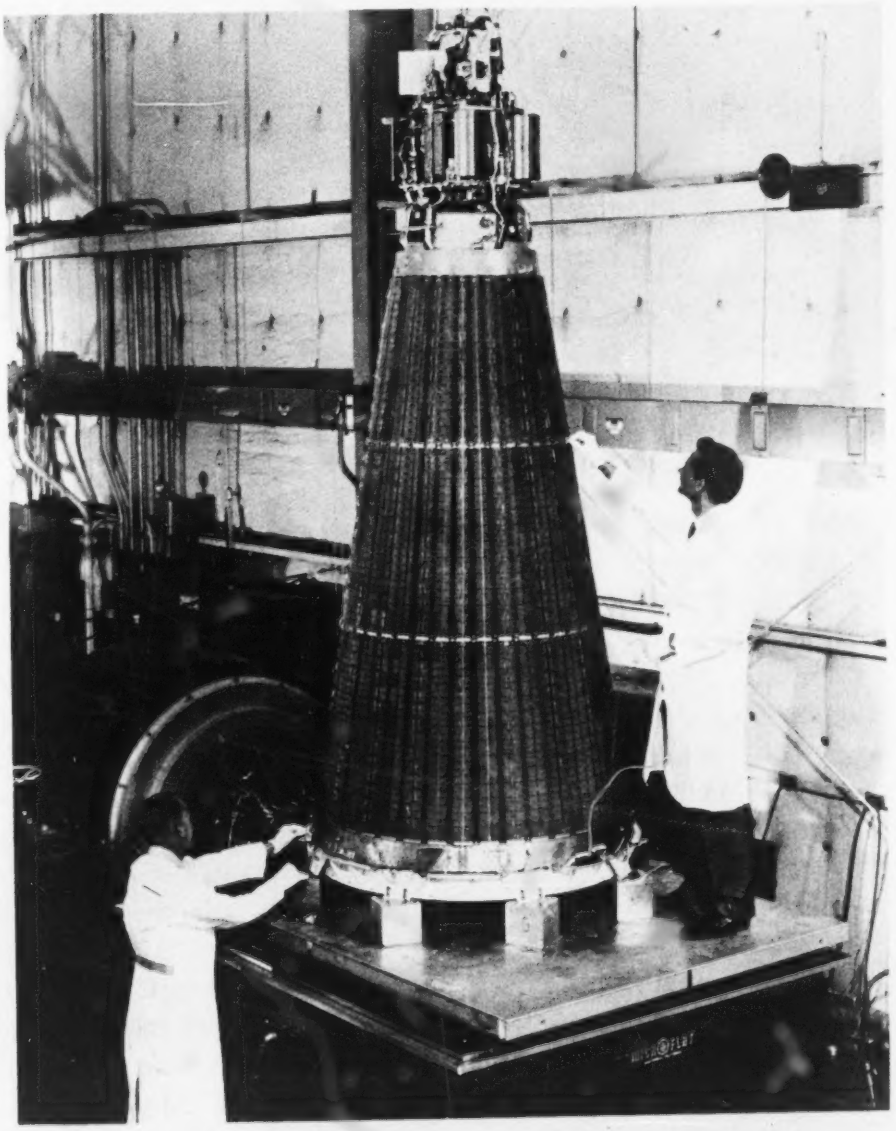

Figure 19 *The complete SNAP-10A power plant showing the reactor perched on top of the conical radiator-thermoelectric element assembly (also shown on the cover). A rocket launch shroud surrounded this power plant during the launch period, but was blown off with explosive bolts once the reactor was in orbit.*

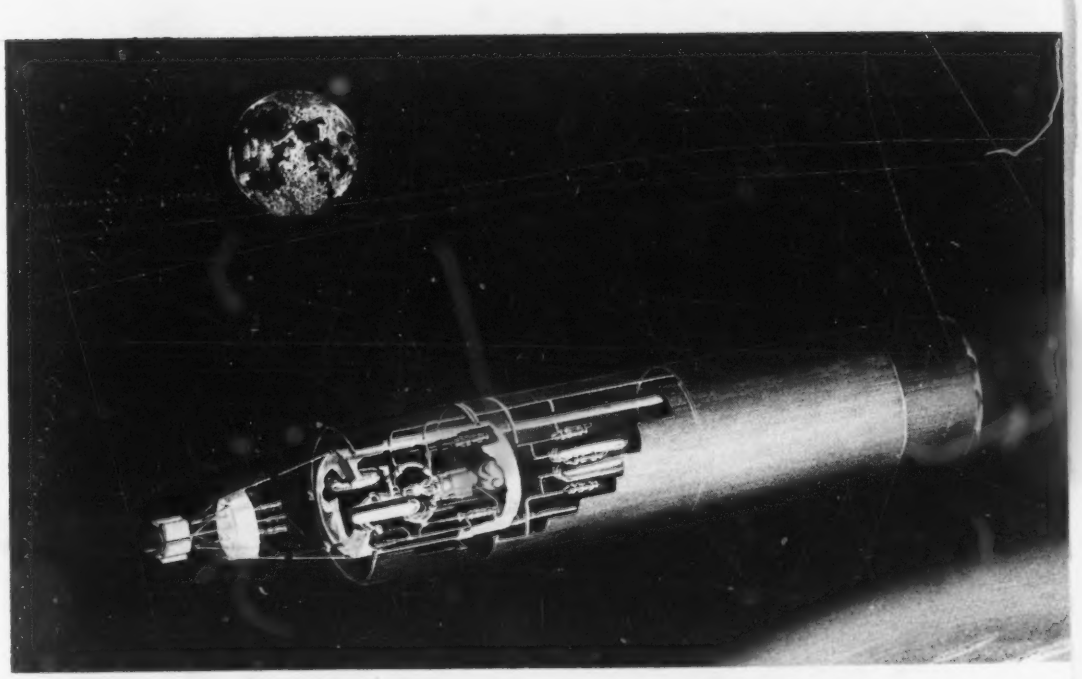

Figure 20 *Artist's conception of a SNAP-50 power plant as it would appear in earth orbit.*

lated at one end of the spacecraft, as shown on many of the diagrams in this booklet. Besides the protection provided by distance, physical shields must often be added to further reduce the neutron and gamma-ray fluxes.* Very dense materials, like lead and tungsten, generally make the best gamma-ray shields, whereas hydrogen-containing (neutron-absorbing) substances, like lithium hydride (LiH) and water, make the best neutron shields. Man is the most sensitive spacecraft cargo; tons of shielding may be needed to protect spacecraft crews from reactor radiation and also from the protons and electrons making up the earth's Van Allen belt.

Where possible, space reactors are shadow shielded only; that is, shielding is placed only between the reactor and the object to be protected. (On earth, reactors must be shielded on all sides because of a scattering of radiation.) Since nuclear radiation in empty space travels in straight

*Nuclear radiation is attenuated, or weakened, in an exponential fashion by shielding. That is, $I = I_0 e^{-\mu t}$, where I = attenuated flux, I_0 = initial flux, μ = absorption coefficient, t = shield thickness, and e = the base of natural logarithms.

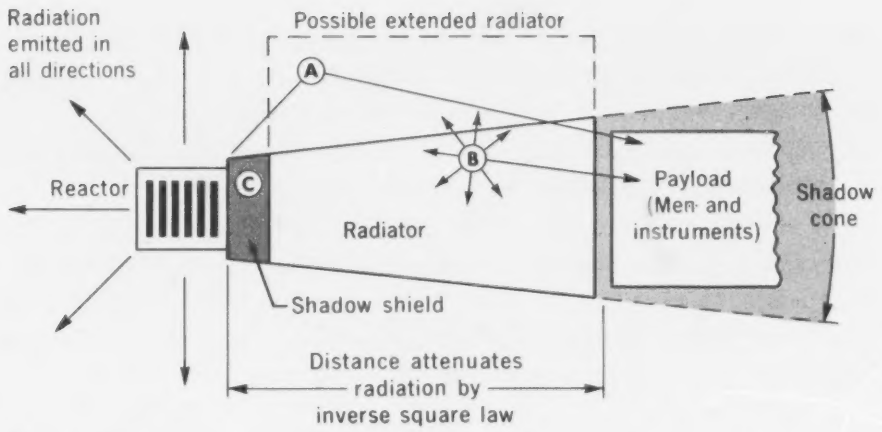

Figure 21 *Shielding problems. Ordinarily, radiation is sufficiently attenuated by a shadow shield. In Case A, however, reactor-produced neutrons may be scattered off an extended radiator or another piece of equipment outside the shadow cone. In Case B, radioactive NaK in the radiator creates a new radiation source on the other side of the shadow shield. Case C shows radiation absorption in the shield.*

lines, men and equipment would be safe in the "shadow"—on the opposite side—of a single piece of shielding. Theoretically a great deal of weight can be saved in this manner. Neutrons, however, might be scattered (reflected) from the radiator (or any other protruding equipment) directly into the shadowed area (see Figure 21), so either the equipment doing the scattering must be shadow shielded or additional shielding must be placed around the sensitive payload.

Let's consider one final shielding topic. If NaK is the liquid-metal reactor coolant, it becomes "activated" (made radioactive) by exposure to reactor neutrons in its repeated passage through the core. More specifically, the natural sodium-23 (^{23}Na) in NaK is transmuted to ^{24}Na by the absorption of a neutron from the fission process. Sodium-24 decays to magnesium-24 (^{24}Mg), with a half-life of 15 hours, by emitting a negative beta particle (electron) and gamma rays. The nuclear equation is

$$^{23}Na_{11} + {}^{1}n_{0} \rightarrow {}^{24}Na_{11} \xrightarrow[15\ hr]{} {}^{24}Mg_{12} + {}^{0}\beta_{1}^{-} + \text{gammas}$$

This coolant radioactivity could cause trouble if the ^{24}Na contained in the NaK is carried through or around the shield

into a heat exchanger or radiator, since the heat exchanger or radiator would then become a source of radiation calling for further shielding, especially on manned spacecraft. One way to minimize this problem would be to use the isotope of potassium that does not become highly activated, ^{39}K, as the reactor coolant for manned systems, instead of NaK. The same thing can be done for lithium, another important liquid-metal coolant in advanced power plant design. Lithium activation can be drastically reduced by using only the lithium-7 isotope present in natural lithium.

Nuclear Safety

The subject of nuclear safety is separate and distinct from reactor shielding. Nuclear-safety analysis anticipates accidents that might occur during the transportation, launch, and operation in space of a nuclear power plant, predicts the probabilities and magnitudes of the risks that might result, and devises ways to avoid them. Theoretically there are three types of potential accidents:

1. Accidental criticality and release of radioactivity due to pre-launch ground handling accidents or launch failures.
2. The accidental widespread dispersal of radioactivity during the reentry into the atmosphere and consumption by air friction* of a nuclear power plant.
3. Accidental exposure of persons to whole reactors or pieces of reactors that have been only partly burned up during reentry after power operation in space.

The possibility that large rocket-launch vehicles theoretically may fall on any spot on earth forces nuclear-power-plant designers to take special pains to ensure built-in safety in addition to the normal safeguards that are designed to protect against reentry accidents. Several practical arrangements are made to meet these theoretical possibilities. Accidents during the transporta-

*This physical process is called "ablation".

tion of the nuclear reactor to the launch pad will not endanger anyone because the nuclear fuel is shipped either in several small packages that cannot be made critical or in a reactor that has so much neutron-absorbing material placed in and around its core that no accident can create criticality.

Once the reactor is on the launch pad, attention shifts to the launch trajectory. A rocket failure could "abort" the mission and could cause the reactor, which still would be cold and subcritical, to strike the earth anywhere along the 5000-mile launch range from Cape Kennedy, Florida, to Ascension Island, far out in the South Atlantic, assuming the launch was made on the Eastern Test Range. Accidental impact of the nonradioactive reactor on one of the scattered, unpopulous islands along the range is unlikely, but, if it did occur, the reactor would break up just like any other piece

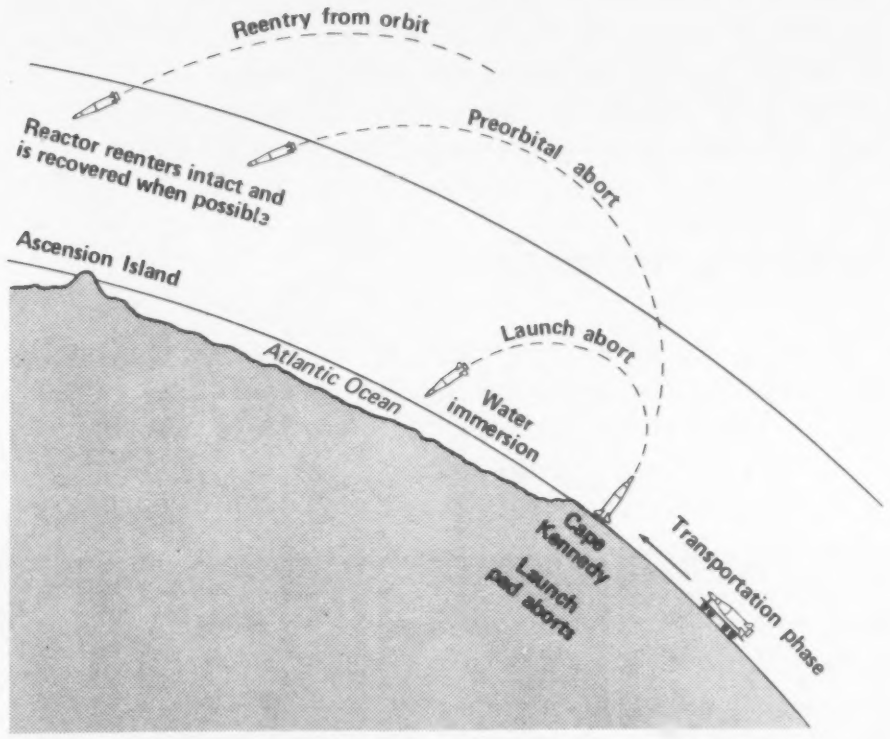

Figure 22 *Possible accidents and situations that nuclear safety engineers must anticipate to guarantee safety.*

of equipment. Since the reactor would not have been operated, the unused uranium fuel would not be dangerous.

Current nuclear safety philosophy insists that space reactors cannot be started up until the launch vehicle has placed them in an orbit higher than 400 miles (640 km). At these altitudes, orbital lifetimes in excess of 100 years are assured and any radioactivity accumulated during power plant operation will have decayed to harmlessly low levels after a century has passed. For example, SNAP-10A, launched in April 1965, circles the earth in an 800-mile (1300-km) orbit, and it will remain there for about 3000 years. If, for some reason, a reactor power plant had to be used in a lower orbit with a lifetime of less than 100 years, a reliable method would have to be found to bring the power plant back from orbit intact to some point on earth where the reactor could be recovered and disposed of safely.

Nuclear safety in space operations is ensured first by an exhaustive search for things that might go wrong. Then the consequences of the accident are computed or determined by actual test. Finally, if the consequences warrant, the power-plant design is altered, or countermeasures are taken to reduce the danger to negligible proportions.

IMPROVING THE BREED

In many areas of technology, a machine is obsolete by the time it is finally put in use. Improvements follow close on the heels of the development of any piece of equipment,

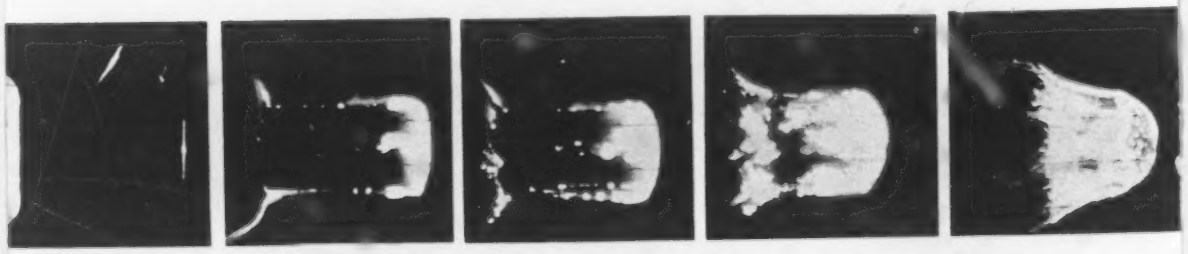

Figure 23 *Ablation of a nose cone in a simulated reentry test.*

whether it is an airplane or a SNAP reactor power plant. Some SNAP improvements are described in the following section.

Boiling Electrons

When SNAP-10A was discussed on page 16, thermoelectric power conversion was described as a relatively inefficient technique. *Thermionic* conversion of heat to electricity, however, promises to overcome this limitation and may therefore replace rotating machinery with direct conversion of energy at high power levels.

The concept of thermionic conversion is this: When an electrode made of a metal like tungsten or molybdenum is heated to a temperature that is high enough, electrons are "boiled off" its surface, just as electrons are thermionically emitted from radio-tube cathodes or electric-bulb filaments. The "hot" electrons are then collected or "condensed" on a cooler collector electrode nearby. A voltage

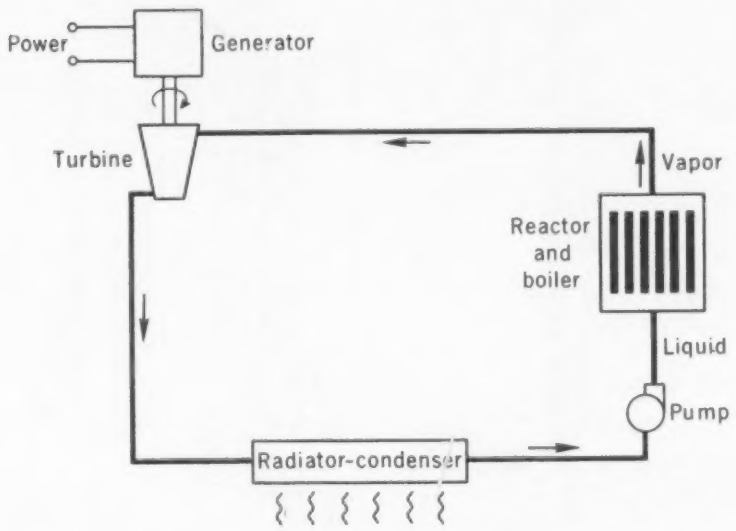

Figure 24 *Schematic diagram of a power plant in which the liquid metal boils directly in the core. The intermediate heat exchanger and primary coolant pump of SNAP-2 and SNAP-8 are thereby eliminated.*

is thus established across the two electrodes, and, of course, the flow of electrons between them constitutes an electrical current. Heat energy is thus converted into electricity. Not all the heat is transformed; most of it is conducted or radiated (as heat) across the narrow gap between the electrodes. This waste heat has to be removed and radiated into empty space, as might be expected.

In principle, the simplest way to make a nuclear thermionic power plant would be to wrap the thermionic-converter emitter right around the reactor fuel element and remove the waste heat with a liquid metal that cools the collector. There are several technical problems encountered with this "in-core" approach:

1. It is difficult to get electrical power out of a core filled with hundreds of interconnected thermionic con-

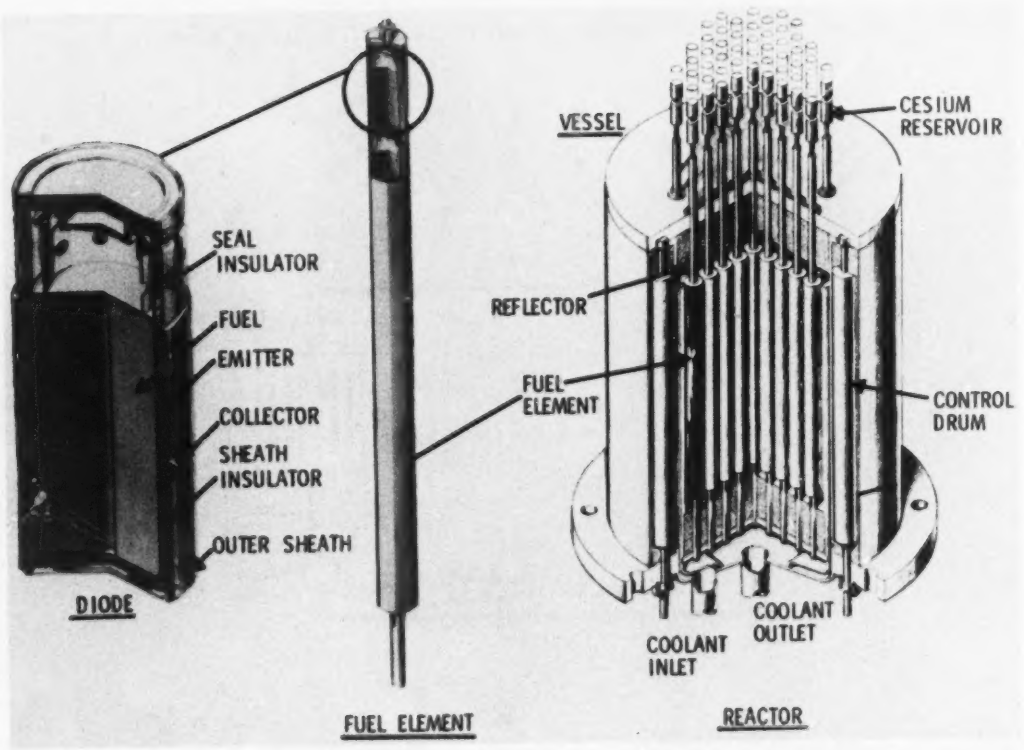

Figure 25 *Thermionic diodes (left) can be assembled like flashlight batteries in long fuel elements (center). The elements are then arranged to make a reactor core as shown on the right.*

verters that are bathed in electrically conducting liquid metal.

2. Thermal contractions and expansions and irradiation damage during reactor operation may cause the tiny gaps between electrodes (0.02 cm) to close and electrically short-circuit the converter.
3. Some of the best thermionic-emitter materials are neutron poisons, which reduce the reactor effectiveness.
4. Common to all thermionic reactor power plants is the extremely high temperature needed to boil electrons off the emitter surface—about 1700°C (3092°F) and up. This temperature requires the use of structural materials with stringent and hard-to-come-by specifications.

Problems like these are well on their way to solution. Electrically heated thermionic diodes have operated successfully for over 3 years; and full-scale thermionic fuel elements have been inserted in reactors, demonstrating the basic feasibility of the concept by operating well over a year without failure. Assemblies of full-scale elements are now being tested in reactors. The in-core thermionic reactor is so promising that the AEC is focussing considerable effort on the concept. With its high conversion efficiencies and low specific weight, the thermionic reactor could well be a very important space power plant during the 1980s and 1990s when we will have large orbiting space stations, large broadcast TV satellites, and, possibly, manned expeditions to Mars.

Brayton Versus Rankine

Early in their studies of the various kinds of space power plants, engineers compared the Rankine cycle with the Brayton, or gas-turbine, cycle,* which is used in jet engines. The Rankine cycle, which is used in SNAP-8

*The two cycles were named after the Scottish engineer, William J. M. Rankine, who also introduced the Rankine temperature scale, and George Brayton, a Philadelphia engineer, who suggested a gas-cycle engine in 1873. The Brayton cycle is also called Joule's cycle in Europe.

(and in all steam engines), involves the alternate boiling and condensing of a two-phase fluid like water or mercury. The Brayton cycle, on the other hand, employs a one-phase (gaseous) fluid like neon or argon to drive the turbines. The diagram for this power plant (Figure 26) shows its conceptual simplicity: Heat the gas in a reactor, expand it through a turbine, cool it in a radiator, compress it, and send it back to the reactor. There is no change of phase from liquid to vapor and back again. There is also the well-developed jet-engine technology to draw upon. Furthermore, the use of an inert gas virtually eliminates the corrosion

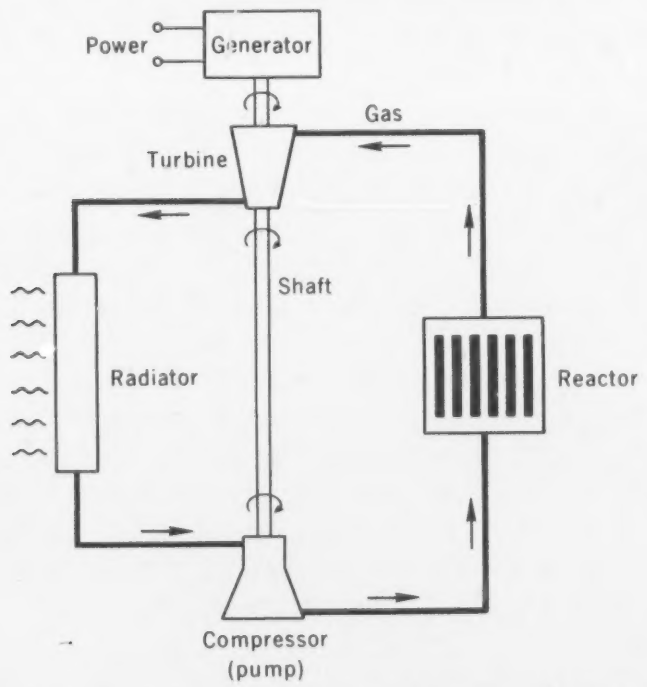

Figure 26 *The Brayton cycle (gas-turbine cycle) nuclear space power plant.*

problem. But—there always is a "but"—two objections arise from a theory and a third from practical considerations:

1. A most important difficulty is the fact that turbine exhaust gases may be easy to cool with the radiator while they are still hot, but, as they progress through the radiator tubes and drop in temperature, there is a

problem that is explained by the Stefan-Boltzmann Law. In the gas, or Brayton, cycle, a large fraction of the heat has to be dissipated at relatively low temperatures; and this requires relatively large and heavy radiators. In contrast, the vapor in the liquid-metal Rankine cycle is condensed at a relatively high, constant temperature; thus a smaller, lighter radiator can be used. (The temperature of a substance remains constant during a change in phase.)

2. A lot of power is needed to compress the low-pressure gas exiting from the radiator back to the pressure level needed at the reactor. The Rankine-cycle liquid-metal pump requires negligible power in comparison.
3. Gas bearings, where a film of gas supports the rotating shaft, have not yet been demonstrated for very long periods of time (more than a year).

The conclusion from the early studies was that Brayton-cycle space power plants would be somewhat heavier than their Rankine-cycle counterparts. Recently, however, there has been a strong upsurge of interest in the gas cycle because of its inherent simplicity and the great technological advances made with aircraft jet engines and in NASA-AEC programs. For example, a Brayton-cycle power-conversion system using helium-xenon has operated successfully for over 2500 hours at the 6-to-10-kilowatt level at 29% efficiency. So successful have been the tests that the Brayton cycle may eventually oust the Rankine cycle as the favored conversion scheme for space power plants.

Basically, there are four Brayton-cycle advantages that outweigh the disadvantages mentioned above:

1. The efficiency is higher than that of the Rankine cycle.
2. The hardware is simpler and it is therefore easier to attain the long lifetimes desired.
3. Because no condensation or boiling processes are involved, the Brayton cycle is easier to design for zero-g operation in space.
4. The Brayton-cycle is more flexible than the Rankine cycle in the sense that it can operate over wider power ranges without hardware changes.

As long as power levels remain below 100 kilowatts, the larger Brayton-cycle radiators are not too important. Since the space missions contemplated for the next few decades require only tens of kilowatts, the future of the Brayton cycle looks bright.

Other Ideas

Several activities now under way aim at improving the present line of space nuclear power plants, rather than seeking the more difficult goal of developing a whole new series of advanced power plants that will use relatively untried techniques.

One such effort involves the development of more effective hydrogen-diffusion barriers to place around the uranium–zirconium–hydride fuel elements used in SNAP-2, SNAP-8, and SNAP-10A. Hydrogen, being a small, chemically active atom, easily seeps through hot metal walls and escapes from the SNAP fuel elements. As hydrogen escapes over a period of time, the reactor neutron economy gets worse because moderating power is lessened. Power-plant lifetime is limited because of this loss of hydrogen moderator.

A second plan attempts to interpose a thermoelectric heat exchanger between a SNAP-10A type reactor and the radiator. The thermoelectric elements are placed within this heat exchanger instead of in the radiator, as in SNAP-10A. A second, nonradioactive coolant carries the waste heat from the heat exchanger to the radiator. The additional weight of the heat exchanger should be more than offset by the reduction in shield weight made possible by the elimination of radioactive NaK from the radiator.

Another type of thermionic reactor power plant is the so-called "out-of-core" system in which the thermionic converters are located in a separate heat exchanger or perhaps directly in the power plant radiator. The aim in this approach is to separate the thermionic problems from those of the reactor. In doing this, the first and third problems listed earlier for the in-core approach are

reduced or eliminated. Reflection shows, however, that the fourth problem is accentuated in the out-of-core design because the liquid metal stream and thus the reactor itself must operate at the high temperatures required for the thermionic emitter surfaces. With the in-core thermionics, the liquid-metal coolant need be only at the much lower thermionic collector temperatures. For this reason, the out-of-core thermionic power plant has been relegated to low priority.

One other possibility for significant performance improvement involves the promising research now under way in thermoelectricity. With new materials and the "cascading" of thermoelectric elements, overall power plant of efficiencies of 7% or higher may be obtainable. In cascading, the heat rejected by a high-temperature thermoelectric element is fed directly into a second thermoelectric element that possesses good low-temperature properties. The two different elements in series perform better than any single element available.

No one can now predict just what kind of nuclear power plant will be used on the first lunar base or on the first manned trip to Mars. But there is little doubt that the key to manned exploration of the solar system is the successful utilization of the energy locked within the uranium nucleus.

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